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Prelude to a study of the aeronomy of the Earth's upper atmosphere

by M. Nicolet

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FOREWORD

This paper will be published later.

AVANT-PROPOS

Ce texte sera publié plus tard.

VOORWOORD

Deze tekst zal later gepubliceerd worden.

VORWORT

Dieser Text wird später veröffentlicht sein.

PRELUDE TO A STUDY OF THE AERONOMY OF THE EARTH'S UPPER ATMOSPHERE

by

MARCEL NICOLET

ABTRACT

Part I.- Before the scientific observations by rockets and satellites.

RESUME

Première partie.- Avant les observations scientifiques par fusées et satellites.

SAMENVATTING

Eerste deel.- Voor de wetenschappelijke observaties door raketten en satellieten.

ZUSAMMENFASSUNG

Erster Teil.- Vor den wissenschaflichen Beobachtungen mit Raketen und Satelliten.

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1.- First Report, 202 pages, 1926.
2.- Second Report, 131 pages, 1929.
3.- Third Report, 132 pages, 1934.
4.- Fourth Report, 154 pages, 1936.
5.- Fifth Report, 203 pages, 1939.
6.- Sixth Report, 215 pages, 1948. From this Report (pages 125-143) : references from the article of M. Nicolet on the absorption of the solar radiation in the high atmosphere.

ATLASES OF THE AIRGLOW SPECTRUM AND OF THE AURORAL SPECTRUM

1. The Airglow Spectrum, 3100-10000Å, by Broadfoot, A.L. and Kendall, K.R., J. Geophys. Res., 72, 426-428, 1968.
2. An atlas of the auroral spectrum, by Vallance Jones, A., Scientific Report No AR-20, 1-8, 1954.

PRELUDE TO A STUDY OF THE AERONOMY OF THE EARTH'S UPPER ATMOSPHERE

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Summary

PART I

Before the scientific observations by rockets and satellites

1. Preliminaries

The use of laughing gas (N_2O) in 1800 (See Figure 1) was followed, 100 years ago, by the detection in the air of the noble gases, helium to xenon.

2. Preamble

After the First World War (1919), in Brussels an official group of International Scientific Unions was created; it included the International Union of Geodesy and Geophysics (IUGG). Before the First World War, hydrogen and helium were not accepted as active atmospheric constituents. However, the noctilucent clouds particularly associated with the Krakatau eruption in 1883 (First Polar Year) were an important height parameter. Nevertheless, Wegener (See Figure 2) introduced his famous geocoronium.

3. Introduction

75 years ago, nitrogen was the principal atmospheric constituent and helium was the unique constituent above 100 km. 70 years ago, the luminosity of meteors led to the suggestion of an increase of temperature with height instead of isothermal layers at -50°C. 65 years ago, the identification of the "green line" to a forbidden transition of atomic oxygen clarified various atmospheric arguments. 50 years ago, the altitudes of the emission of the airglow lines were still fixed above 200 km while the sunlit auroras detected by Störmer were a demonstration of the existence of molecular nitrogen at 1000 km.

4. Sun and Ionosphere before 1940

The first systematic observations (1939) of various ionospheric layers (D, E, F_1, F_2) were new means for a development of the aeronomy of the Earth's upper atmosphere. The E layer at an altitude of the order of 100km was considered as a typical ionospheric region since the diurnal variation of the maximum electron density changed synchronously with the solar zenith distance. Furthermore, the general variation of the maximum electron peak at noon (of the order of 10^5 electrons cm^{-3}) showed an effect of solar activity that is revealed, for example, in the arbitrary numbers used to characterize the facular plages of ionized calcium Ca^+.

The diurnal behavior of the ionization state of the F_1 region was found in part to be identical to that of the E layer. But the electron density (not less than 10^6 electrons cm^{-3}) of the F_2 region was characterized by irregular rhythms explained later by technical effects and scientific reasons.

The Marconi link by long waves over the Atlantic Ocean near 1900 led to the hypothesis of a normal D region situated below the E layer. It was explained (before any atmospheric observation) by the chromospheric emission of H-Lyman-α ionizing nitric oxide, NO. This molecule was produced by a special atmospheric reaction.

5. Before the first analysis of scientific results obtained by rockets

Two international meetings were organized, in 1947,

(1) by the Gassiot Committee of the Physical Society in London on the emission of the spectra of the night sky and auroras (25 papers published in 1948).

(2) by the Centre National de la Recherche Scientifique in Lyon on the relations between solar and terrestrial phenomena (40 papers published in 1948).

In 1948 the general assemblies of the International Union of Geodesy and Geophysics and of the International Astronomical Union were held in Oslo and in Zurich, respectively. Results obtained during World War II were discussed. For example, they included the influx of atomic hydrogen observed in various lines ($H\alpha$) of auroras and many details of the spectrum of the night sky. The results obtained by radar during the War were also an important addition to the knowledge of the microwave solar radiation.

6. A new step forward

The observation by Elvey and Roach of strong radiations in the infrared airglow, identified by Meinel with OH bands, led Bates and Nicolet to the introduction of specific reactions by atomic hydrogen and that would apply ozone below 100 km. This consideration of the importance of such reactions was the step needed for new aspects to be introduced in the aeronomic study of the Earth's upper atmosphere.

1.- Preliminaries

100 years ago, the kinetic theory of gases (Boltzmann, Maxwell) was sufficiently well known for it to be applied to the Earth's atmosphere. But the chemical composition and the physical constitution of our Atmosphere were not yet topic for which a meaningful concoction of detailed observations could be made.

In the eighteenth century, two gases, oxygen and nitrogen were known (Cavendish, Lavoisier, Priestley, ..). In addition, the nitrogen oxides were produced (Cavendish) in a discharge of dry air and oxygen. Laughing gas (N_2O) is a famous example (See Figure 1, Davy 1801). On the other hand, it was only one hundred years ago that the first noble gases were discovered : helium [ἡλιος = sun] (Lockyer, line not identified in the solar spectrum) and argon [αργος -ον = inactive, Ramsay]. Argon being ^{40}A and not ^{36}A is a radioactive product, along with ^{40}Ca, ^{40}Kr in the Earth's interior. The detection (1898) of the other noble gases came afterwards thanks to "liquid air" : krypton [χρνπτον = hidden], neon [νεον = new) and xenon [ξενον = strange].

During the 19th century, scientific observations were very limited, because the technical means for vertical prospecting with height of the Atmosphere did not exist. Meteors and the effect of their destruction in the high atmosphere were not yet studied. Radioelectric wave propagation was not yet known nor associated with the existence of an ionosphere. The spectroscopic observation of the aurora was at its beginning, even though this polar phenomenon had attracted many visual observers. But if the spectroscopic observation had detected auroral radiations, spectroscopic knowledge itself was still in an embryonic stage.

Figure 1.- Humphrey Davy studied the effects of nitrous oxide, or "laughing gas", on himself and others, and in 1808 published the results of his research. He realized the painkilling effects of the gas meant that it might have medical uses. This drawing by James Gillray shows Davy lecturing on nitrous oxide at the Royal Institution, on 20 June 1801. Davy holds the bellows, while his associate prepares to administer nitrous oxide to a member of the audience. The volunteer so enjoyed inhaling the gas that the breathing bag had to be taken away from him by force. (Photo courtesy of Yale Medical Library).

2. Preamble

Seventy-five years ago, several national Committees of Geophysics were founded in association with the creation in Brussels of the International Union of Geodesy and Geophysics (IUGG), with six Sections, as a member of the International Research Council, which itself became the International Council of Scientific Unions in 1931 (See the address presented during the meeting of the General Committee of the International Council of Scientific Unions on Thursday, 5 July 1979, at the Château de Laeken on the invitation of Their Majesties the King and the Queen of Belgians; Nicolet 1980).

In 1919, after the First World War, the upper atmosphere had not yet been investigated experimentally. The stratosphere had sometimes been observed up to 35 km with meteorological balloons to show that there was a limit to the adiabatic decrease of temperature in the troposphere (Teisserenc de Bort, 1898). All researches, therefore, had to invoke theory in order to find out the upper atmospheric conditions. Attempts to explain the origin of possible physical mechanisms led to various scenarios that were used to explain several of the observed features with relative plausibility.

In 1910, Jeans considered that above 10 kilometers the atmosphere was in isothermal equilibrium. His personal conclusions (1910) were that "hydrogen passes nitrogen at about 95 kilometers up, while at 100 kilometers the hydrogen forms 90 percent of the whole atmosphere, and at 800 kilometers, the atmosphere is entirely hydrogen, except for an infinitesimal trace of helium. The helium in the atmosphere is at no point any great proportion of the whole".

In 1911, Wegener, after having considered the spectral phenomena that were characteristic of the aurora and airglow (night-sky spectrum) and has been published in over a hundred publications since the early work of Angström in 1896, made the suggestion that the green line easily observed in the visible spectrum was produced by a very light constituent, the "geocoronium". Its mass 0.4, compared to hydrogen H_2 = 2, led him to suggest that above a sphere of hydrogen, 75 km to 210 km, there was a sphere of geocoronium up to more than 500 km where helium did not play any role (see Figure 2). But the hypothesis advanced by Wegener (1911a) that besides hydrogen there was this still lighter constituent (geocoronium, by analogy with the coronal lines only identified in 1940) was not generally accepted, because of the impossibility that the earth's atmosphere could retain a gas with such low molecular weight, and this in an era when hydrogen and helium were not yet accepted as active constituents. Nevertheless Wegener (1911b) in his book entitled "Thermodynamik der Atmosphäre" considered the problems of the noctilucent clouds observed by Jesse (1887) after ground sunset generally between 80 and 85 km (Jesse, 1896), and also of the Krakatoa volcanic eruption during the First International Polar Year 1882-1883.

A description of "Noctilucent Clouds" has been published recently by Gadsden and Schröder (1989). This book, drawn on about 550 references, and considers many aspects. As nautical twilight deepens the color of the noctilucent clouds soon appears blue, became of the oblique absorption effect of the Chappuis bands of atmospheric ozone. The simultaneous presence of dust particles and terrestrial H_2O between 80 and 85 km is associated with the formation of clouds consisting of ice coated extraterrestrial dust particles that scatter sunlight at low temperatures.

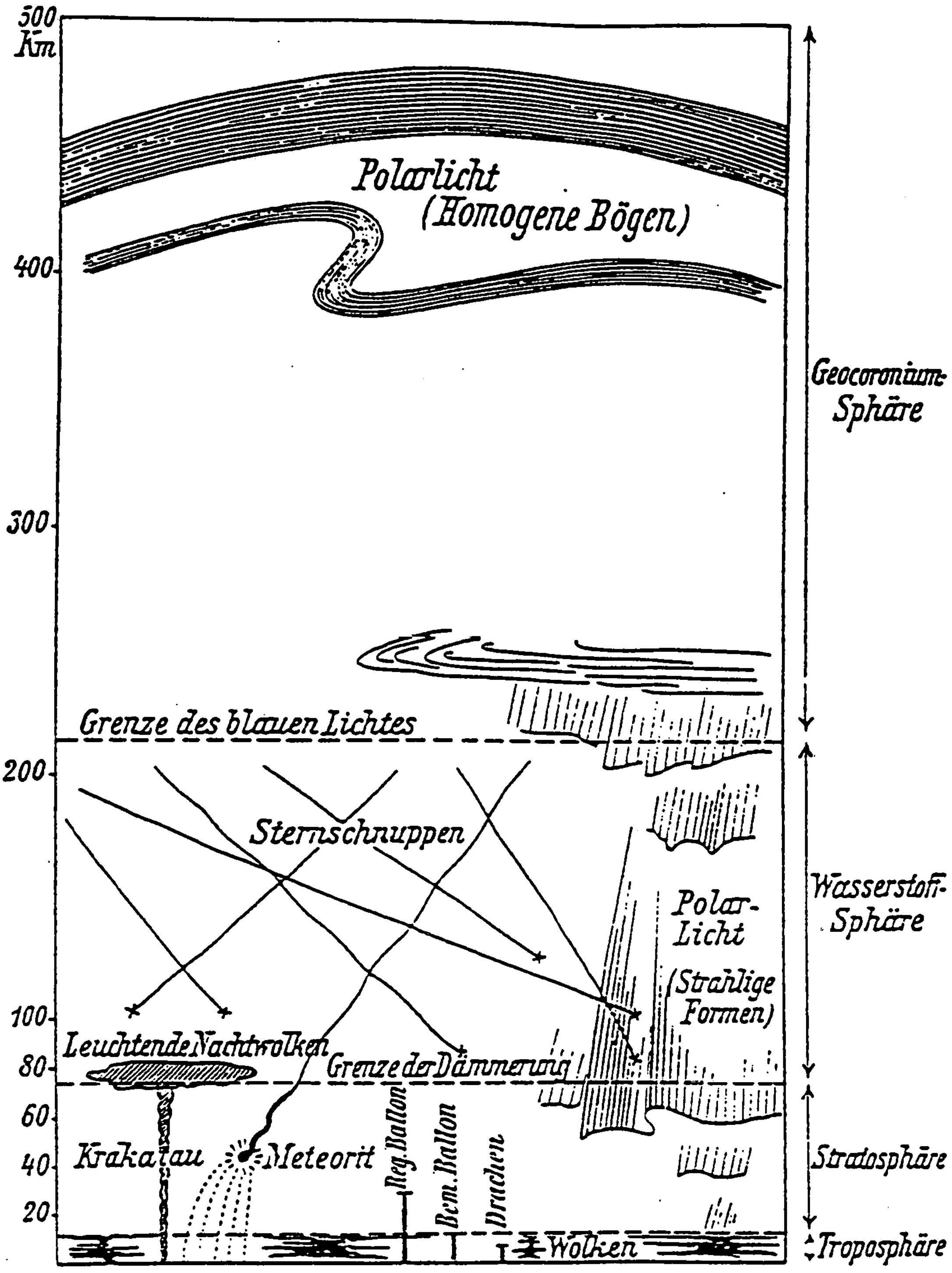

Figure 2.- The composition and structure of the Earth's atmosphere according to Wegener (1911a,b). The stratosphere is limited at the altitude of the noctilucent clouds. The Krakatau eruption is considered. The region characterized by molecular hydrogen is also the region of meteors and of the aurora polaris. From 200 km up to more than 500 km the region of the geocoronium is characterized by the high activity of the aurora and the presence in the visible of the green line that was only first identified in 1928.

A complete account of almost 500 pages of the Krakatau eruption in August 1883 and its spectacular atmospheric optical phenomena, was published ten years ago by Simkin and Fiske (1983). In their general description, many geographical and geophysical aspects were considered. In the increased worldwide twilight phenomena in 1883-1885 there were unusual visible afterglows that many pastels have illustrated.

Today we have associated the Krakatoa twilights and the noctilucent cloud phenomena with the thermal behavior of the mesosphere. Extremely low temperatures at the mesopause may range, for example, from 130 to 140°K near 85 km.

3. Introduction

75 years ago, Chapman and Milne had undertaken a calculation of the composition and structure of the upper atmosphere that was published under the title of "The Composition, Ionization and Viscosity of the Atmosphere at "Great Heights" (Chapman and Milne, 1920). At that time, the "green line" was of unknown origin, and no hydrogen or helium line was known to appear in the auroral spectra, although the earth's atmosphere was deemed to retain hydrogen, and therefore all heavier constituents. But gases of molecular weight less than unity would not have been retained (geocoronium, for example).

The general conclusion which came from the results of this paper was that nitrogen only reached an altitude of 150 km and that above 150 km helium was the normal and unique constituent.

A few years later, 70 years ago, Lindeman and Dobson (1923) made a detailed analysis of the luminosity of meteors, and their conclusion was that the temperature increased from its value of something like 220°K to highest temperatures of perhaps 300°K. Their explanation based on the radiative properties of ozone was correct, but unfortunately the height of the phenomenon was placed above 60 km. Today we know that there is a temperature minimum at the mesopause where the noctilucent clouds are observed. Nevertheless, after the publication of Lindeman and Dobson (1923), Whipple (1923) suggested that their results had provided an explanation of the occurence of zones of audibility and zones of silence surrounding the scenes of great explosions. Whipple (1923) wrote also that "further progresses in our knowledge of the temperature of the outer atmosphere and of its motion would be made if Prof. Goddard could send up his rockets. The times of passage of sound waves from the bursting rockets would give immediate information as to the temperature of the air. Perhaps it would be more practicable to use a Big Bertha to send up a bursting shell". Moreover, Whipple (1929) wrote a detailed article on "the propagation of airwaves at great distances and indication of conditions in the upper atmosphere". With reference to this subject, the publications by de Quervain (1908) on the dynamite explosion at the "Jungfraubahn" on 15 November 1908 and by V.d. Borne (1910) on the dispersion of the sound waves should be considered.

From the preceding discussion it is apparent that the structure and composition of the earth's upper atmosphere were not understood. In his study of the propagation of radio waves, Pedersen (1927) adopted a representation of the atmosphere up to 200 km with a constant temperature of about - 50°C above 10 km, and with only 10% of oxygen and nitrogen at 80 km and 130 km, respectively. But during the same period, the green line at 5577 Å was identified as an oxygen line by McLennan and Schrum (1925) and finally attributed to an electronic transition from the ^1S_o to ^1D metastable levels of oxygen atoms by McLennan et al (1928).

During the same period the first general conference on atmospheric ozone and the atmospheric absorption was convened in 1928 in Paris by Fabry (1929). Dobson (1929) gave a general description of his measurement of atmospheric ozone and its association with meteorological and geographical conditions. Chalonge and Götz (1929) demonstrated that there was no variation between day and night of the ozone content in the stratosphere. Chapman (1929) gave a short abstract of the variation of ozone in the upper atmosphere, an introduction to his general paper published one year later (1930). The period covered by the work of pioneers of spectroscopic determinations in the atmosphere is described by Nicolet (1979, pages 27-97), based on more than 200 publications.

Before the Second World War, the knowledge of the composition and structure of the upper atmosphere was essentially based on knowledge of atmospheric spectra and the propagation of radio waves. General publications by Déjardin (1936) on the light of the night sky (airglow), by Hewson (1937) on the characteristics and spectra of the aurora, and by Mimno (1937) on the ionosphere, give an idea of the general knowledge before 1940, about 50 years ago.

The study of meteors was, however, developed by Fred Whipple (1938,...., 1940) at Harvard and led to important results that cannot be described in this article because the astrophysical part of the problem is too important for the present analysis. Nevertheless, additional information can be found in a relatively recent publication under the direction of Fred L. Whipple (1967) with 48 articles in the Smithsonian Contribution to Astrophysics.

50 years ago, the altitude of the emission of the airglow lines was fixed between 200 and 300 km. Because the lines of hydrogen and helium were not detected the conclusion was that there was no dominating layer of light gases floating at the top of the atmosphere. The spectrum of N_2 detected by Störmer (1929) in the sunlit aurorae at great heights above 500 km was not taken as an extremely important atmospheric phenomenon to be interpreted as showing the presence of molecular nitrogen at high altitudes.

In 1925, a new international commission appointed by the "International Research Council for the Study of solar and terrestrial relationsphips" (Chairman : S. Chapman) (see 1926) for the study of solar and terrestrial relationships met in Brussels and had close contact with the Section of Terrestrial Magnetism and Atmospheric Electricity of the IUGG. Following a first and introductory report with about 100 references on various subjects (1926), three years later the second report was published (see references 1929); it included several memoranda such as the problem of the solar constant (Abbot, 1929) with its irregular variations and its absolute value. In fact, the solar constant has always been considered as having a value of the order of 1.95 cal min^{-1} cm^{-2} within ± 2.5%; see for example, Unsöld (Chapter II on the solar a radiation and its measurements, pages 21 to 40, 1938). The article by Whipple (1929) on the propagation of airwaves at great distance is also a part of this volume and that provided an indication of physical conditions in the atmosphere in 1929. In the third report (corresponding to the beginning of the International Second Polar Year 1932-1933), Douglas (1932) published a paper on tree growth and solar cycles, an example of the great diversity of articles. But it must be added that McLennan (1932) gave a complete account on the problem of the auroral green line. In 1936, in the fourth report of the Commission (1932-1935) may be found as last article a summary, by Brooks (1936), of the results obtained from 1925 to 1934 on relations between meteorological and solar phenomena, a problem which has a long life. The fifth report covered the years 1936 to 1938 and corresponded to a period of sunspot maximum (1937-1938); it led to new developments in the analysis of radioelectric wave propagation. The existence of various regions or layers (D, E, F_1, F_2, ..) was considered with their variations (Appleton, 1939). The ionospheric disturbances related to the solar eruptions (Stratton, 1939; Waldmeier, 1939; Dellinger, 1939; and Berkner, 1939a; for example) were analyzed with their different aspects such as the fade-out of short waves and the amplification of long radiowaves. Figure 3 is a typical example of a short wave fade-out shown by Berkner (1939a) from the variation of the critical frequency at Watheroo, Australia, in September 1938. The altitudes correspond to virtual heights and were still subject to misleading interpretation. For a correct interpretation see, for example, Kelso (1952).

The multiple problems related to terrestrial magnetism and atmospheric electricity were described in a book of 793 pages edited by Fleming in 1939. In his article (Chapter XI, pages 434 to 491) on "radio exploration of the earth's outer atmosphere" Berkner (1939b) wrote as a fundamental remark that "there is a good reason to believe that the virtual height is not greatly different from the actual height over most of the record, limits of the exceptions being uniquely defined by the record itself". (This story did not prove out). In Chapter X (pages 492 to 572), Hulburt (1939) in an article on the upper atmosphere indicated that Maris (1928, 1929) had considered the problem of diffusion above 100 km, but insisted that many aspects of upper atmosphere behavior had not yet been considered. However, an important problem was resolved during this period : the exact vertical distribution of stratospheric ozone, thanks to the discovery of the "Umkehr-effect" by Götz (1931) and its application to

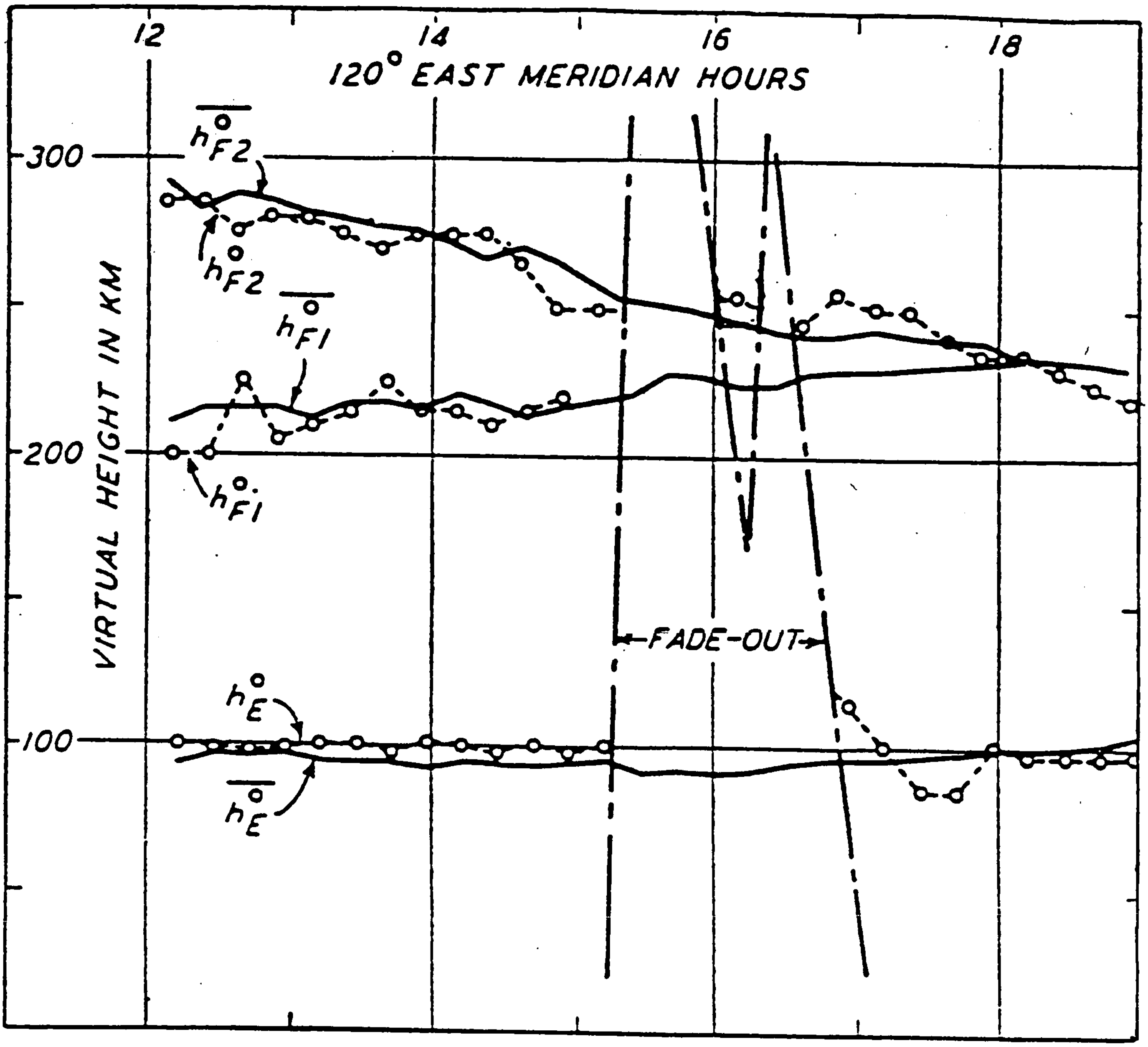

Figure 3.- Virtual heights (Berkner, 1939a) in the ionosphere showing the effect of a radio fade-out in September 20, 1938, determined from automatic multifrequency recordings at Watheroo Magnetic Observatory (116° East, 30° South) Western Australia.

direct observations made in Arosa with the various Dobson instruments (Götz et al., 1934). The study of the effect of secondary scattering and of refraction of solar rays for this problem was carried out with numerical rigor by Chapman (1935). The vertical distribution of ozone was determined, with a maximum concentration below 30 km in the stratosphere. This was a significant drop from 100 km, where O_3 had been introduced to account for its geophysical effects.

In a detailed description on the aurora polaris and the upper atmosphere (Chapter XI, pages 573 to 656) L. Vegard (1939) claimed that the layer of light gases (hydrogen and helium), which had been supposed to be present at the top of our atmosphere, did not exist.

As for auroral problems, the observational results obtained by C. Störmer were fundamental. Already in 1929, he had noticed the distribution in space of the sunlit auroral rays (1929a), the action of sunlight (1929b), and the difference between the spectrum of sunlit auroral rays above 500 km and the spectrum of the lower aurora in the Earth's shadow (1929c). The bands of N_2^+ at 4278 and 3914 Å, which give the blue and violet colours to the rays, were very much stronger than any other auroral line or band, (Störmer, 1929, 1930, 1939). No line of helium or hydrogen was observed in the spectrum of these high rays. During the period of maximum solar activity 1938-1939, before the Second World War, Störmer (1939) observed many sunlit auroras with their N_2^+ bands (See Figure 4). A complete description was given 10 years later when Störmer (1949) provided a detailed description of his observations since 1911. Since I had made (Nicolet, 1937) the first identification in cometary spectra of the emission lines of the CH molecule resulting from a resonance-fluorescence process, I concluded that the process was identical for the resonance system of

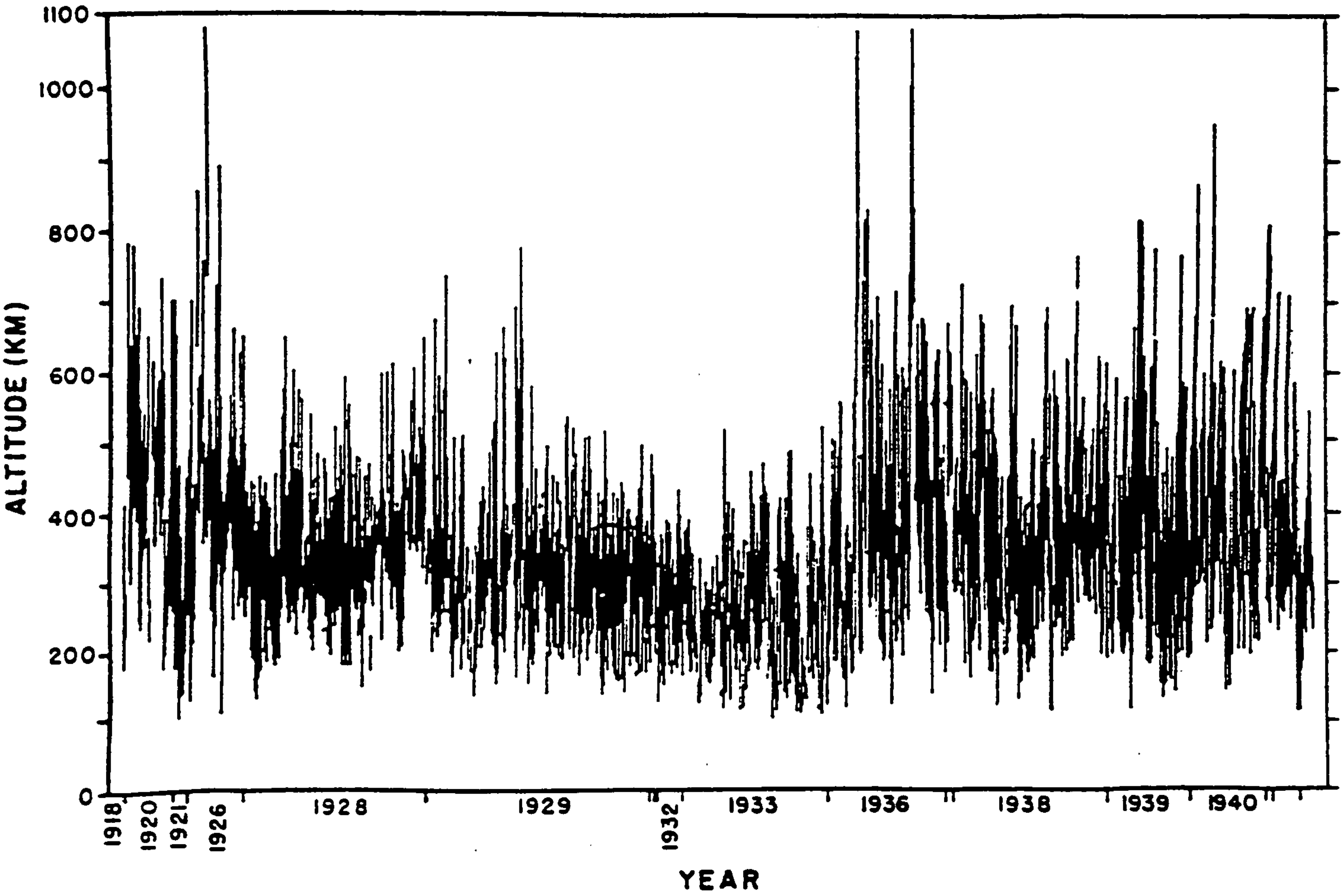

Figure 4.- Sunlit Aurorae by Störmer. From 1936 to 1939, they were observed during a period of high solar activity and characterized by the high altitude of auroral rays. They are the result of the emission of the bands of the ionized molecules N_2^+ due to a resonance fluorescence process in the solar radiation field with a short life time of about 2×10^{-8} sec. A piece of evidence of molecular nitrogen at 1000 km.

than N2 and, therefore, that molecular nitrogen was a normal constituent of the atmosphere at great heights. But, I implicitely assumed that the oscillator strength was not too small a fraction. Detailed discussions were published later by Bates (1949a,b) and Shull (1950) to show that the oscillator strength was near f = 0.12 corresponding to a radiative life time $\tau_{N_2^+} = 2 \times 10^{-8}$ sec.

4. Sun and Ionosphere before 1940

In 1901, Marconi established the first radio link between Poldhu in Cornwall and Saint-Jean-de Terre-Neuve. The success of this transmission reinstated the hypothesis (near 1880) of Stewart and (near 1890) of Schuster who had suggested that a part of the earth's magnetic field results from electrical currents in the upper atmosphere. Indeed, in 1902, Kennelly and Heaviside simultaneously proposed the existence of a conducting layer involved in the propagation of electromagnetic waves, whereas the work of Lord Rayleigh (1903) and Poincaré (1903) revealed the impossibility of explaining the sucess of Marconi's experiment by diffraction. By introducing the ionization effect caused by solar radiation, Eccles proposed the fundamental theory of wave propagation in an ionized medium. Meanwhile, after having carried out experiments on the variation in reception intensity with distance from the broadcasting station, Austin derived an empirical formula that was later rederived by Watson, who solved the mathematical problem of wave propagation in a medium bounded by two concentric spheres. The hypothesis of a conducting layer in the upper atmosphere was thus verified. Several years of rather disorderly experiments contributed some more refinements to the behavior of waves when, after 10 years, Larmor extended Eccles' theory to study the propagation of radiowaves in a very rarefied medium (absence of collisions) without external influence. One year later, Appleton (and Nicholls and Schelleng) completed this theory by introducing the influences of the earth's magnetic field (magnetoionic theory). The following year, the influence of molecular collisions on the propagation was studied by Lassen. The introduction of this effect of frictional forces between neutral and charged particles revealed the relationship between the propagation and absorption of waves in the atmosphere. Finally, in 1927, Appleton gave a complete theory of the propagation of electromagnetic waves in a medium composed of charged and neutral particles subject to the effect of collisions in the presence of a magnetic field.

This last work concluded the preliminary period of research. Experimentation was soon to benefit from new methods applicable to a systematic investigation of radio waves. The magnetoionic theory was born and would be developed for the purpose of studying the propagation of waves in the atmosphere. The physical study of the ionosphere was ready to begin.

In fact, it is not surprising that knowledge of the solar spectral irradiance, which is required for an aeronomic study of the ionosphere, was based on a few inferences of an indirect nature; beyond that nothing was known for certain. The photographic method for solar observation was introduced by Janssen in 1873 and led to the first detailed reproduction of the solar granulation of the photosphere (light sphere = bright surface of the sun). But, before in 1814, after the first discovery (1808) by Wollaston, Fraunhofer transmitted the results of his spectroscopic observations of photospheric dark lines that result from absorption by various atoms. The spectroheliograph (Hale and Deslandres in 1891) introduced the possibility of studying the solar atmosphere at various levels (chromosphere) above the photosphere. A visual observation in 1859 by Carrington of a solar flare led to the first study of its terrestrial influence as detected by a magnetic effect. Many years later solar flares were associated with ionospheric fade-outs. The introduction of the spectroheliscope (Hale) made possible a monochromatic study of solar flares at various terrestrial latitudes and longitudes in order to obtain a permanent solar record. Finally, in 1930, observation of the coronal radiation became possible thanks to the coronograph of Bernard Lyot.

An exact or detailed description of the solar phenomena cannot be given prior to 1940 because the spectral observations were limited near 2900 to 3000 Å by the ultraviolet absorption of the atmospheric molecules O_2 and O_3. Therefore, interpretations of all ionospheric phenomena depending on the action of ultraviolet and X-ray radiations were often based on fallacious reasoning. The radio-emission was not yet known. Hence, it was necessary to refer only to sunspot numbers as a direct index of solar activity, with the addition of the faculae and of the particular results deduced from spectroheliscopic observations. For a descriptive portrayal of the various solar conditions known before the Second World War (see, for example Nicolet, 1943 with about 150 references). Today, this kind of solar activity data involving the daily sunspot relative numbers from Zürich for 1850-1980 and the international daily sunspot numbers for 1981-1993 can be found at the Royal Observatory of Belgium, Uccle, Brussels with their monthly means, the smoothed monthly means based on 13 months and the yearly means.

On the other hand, parallel to the development of the mathematical theory of radiowaves in the atmosphere, experimental investigations had undergone improvements which provided various means of exploring the ionosphere. The echo method of Breit and Tuve, the study of the minimum range of short waves by Hulburt, and the examination of the interference of "reflected" waves by Appleton initiated the first fruitful investigations of the ionosphere. Furthermore, the echo method was adapted to automatic recording and served for a daily determination of the normal characteristics of the ionosphere, of the equivalent or virtual height, and of the critical frequency.

The echo method consists in the quasi-vertical emission of very brief signals which are received at a short distance from the emitter. The time t between the respective receptions of the wave from the ground and of the wave "returned" by the atmosphere makes it possible to measure the equivalent height z of an ionized region by the relation $z = tc/2$ where c is the velocity of the wave. In addition, if the vertical soundings are performed at increasing frequencies, one finds that, for certain frequency intervals, the equivalent heights are more or less constant and thus define distinct ionized regions. Passage from one region to another is characterized by an abrupt change in the equivalent height. The frequencies, associated with these changes were called critical frequencies, corresponding to a maximum number of electrons. The use of these automatic observational systems made it possible to obtain continuous experimental results at various points on the globe. We may cite, in 1939, the stations at Washington, D.C., at Huancayo, Peru near the magnetic equator, at Watheroo, Australia in the Southern hemisphere, and at Tromsö, Norway in Northern latitudes, whose regular publications, before the Second World War, permitted the first systematic study of the characteristic properties of the ionosphere.

In general, observations revealed the presence of two principal ionized regions called the E and F regions. The first region, E, was situated at an altitude close to or somewhat above 100 km, whereas the F region was often subdivided into the two regions F_1 and F_2 located at altitudes of the order of 200-250 km and 300-400 km, respectively. The heights of these ionization maxima represented average values which varied with the latitude and the seasons.

In a particular case (for example, near the Equator) the vertical distribution was succinctly described as follows (see Figure 5a) : near the ground, cosmic and terrestrial sources produce a few thousand ions per cm^3. As one goes up into the troposphere and stratosphere the ion concentration increases up to an altitude of about 18 km. Starting from 60 km, the observational results indicated the existence of an ill-defined region generally referred to as the D region.

At about 100 km, the increase is so considerable that the maximum concentration reached was of the order of 10^5 electrons; this was the E region. Beyond 100 km, the ionization, after a slight decrease, increased again and reached a high value which exceeded that of the E layer (approximately double); this was the F_1 layer.

After a slight decrease, the most important maximum appeared corresponding to the F_2 layer with an electronic concentration exceeding 10^6 electrons per cm^3.

In the D region, an ionization of a few hundred to one thousand electrons per cm^3 was needed for the return of long waves of several km. During a sudden fade-out of short wave propagation (see figure 3) an increase of ionization occurred in the D region, since there was an amplification of the return of long waves. Such phenomena required very short solar wavelengths not yet observed, or a chromospheric radiation subject to the solar activity effect, but not the

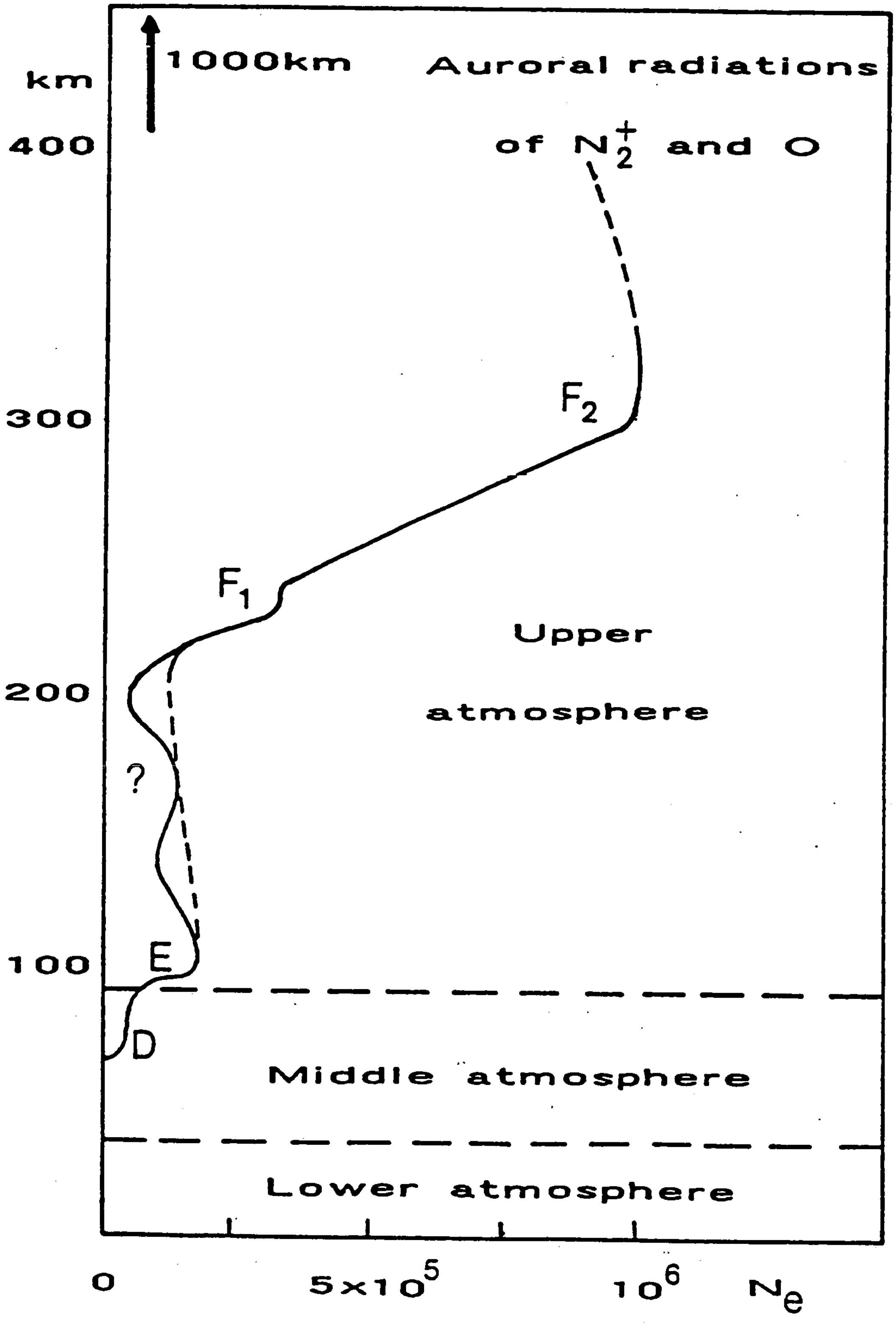

Figure 5a.- Schematic representation in 1939 of the ionosphere with the electron concentration (number of electrons per cm^3) related to the vertical height (km).

absorbed in the E and F layers; therefore, a wavelength greater than 1000 Å. The radiation Lyman-α (1216 Å), which is associated with the chromospheric line Hα, can ionize only the molecule NO, with a low ionization potential, which must be introduced as a minor constituent below 100 km. The ionization potential of NO is less than those of O_2, N_2, O, ... which must participate in the ionization of the E and F regions.

The E region is an ionized layer whose properties were known fairly well before World War II, since its different variations are relatively simple. Figure 5b shows a typical curve of the maximum electron concentration at Washington, D.C. for May 1938. This concentration varies synchronously with the height of the sun above the horizon. Therefore, the following conclusions were drawn directly from the observation (1) the diurnal ionization maximum takes place at noon when the height of the sun is maximum; (2) the value $(n_e)_{max}$ is practically symmetrical with respect to noon. In short, the observations yield the law

$$(n_e)_{max} = C\ (\sin h_\odot)^x$$

so long as $h_\odot > 0°$. The meaning of the constant C was obtaine by setting $h_\odot = 90°$and corresponds, therefore, to the maximum electron concentration of the E layer at the Equator and at the Equinox. Although all the stations distributed over the globe presented the same kind of diurnal and seasonal variations it was clear that the atmospheric conditions that are functions of latitude had to be added to the solar effect itself. In any case, the variation of the maximum electron concentration of the E layer indicated that the electronic recombination was almost instantaneous.

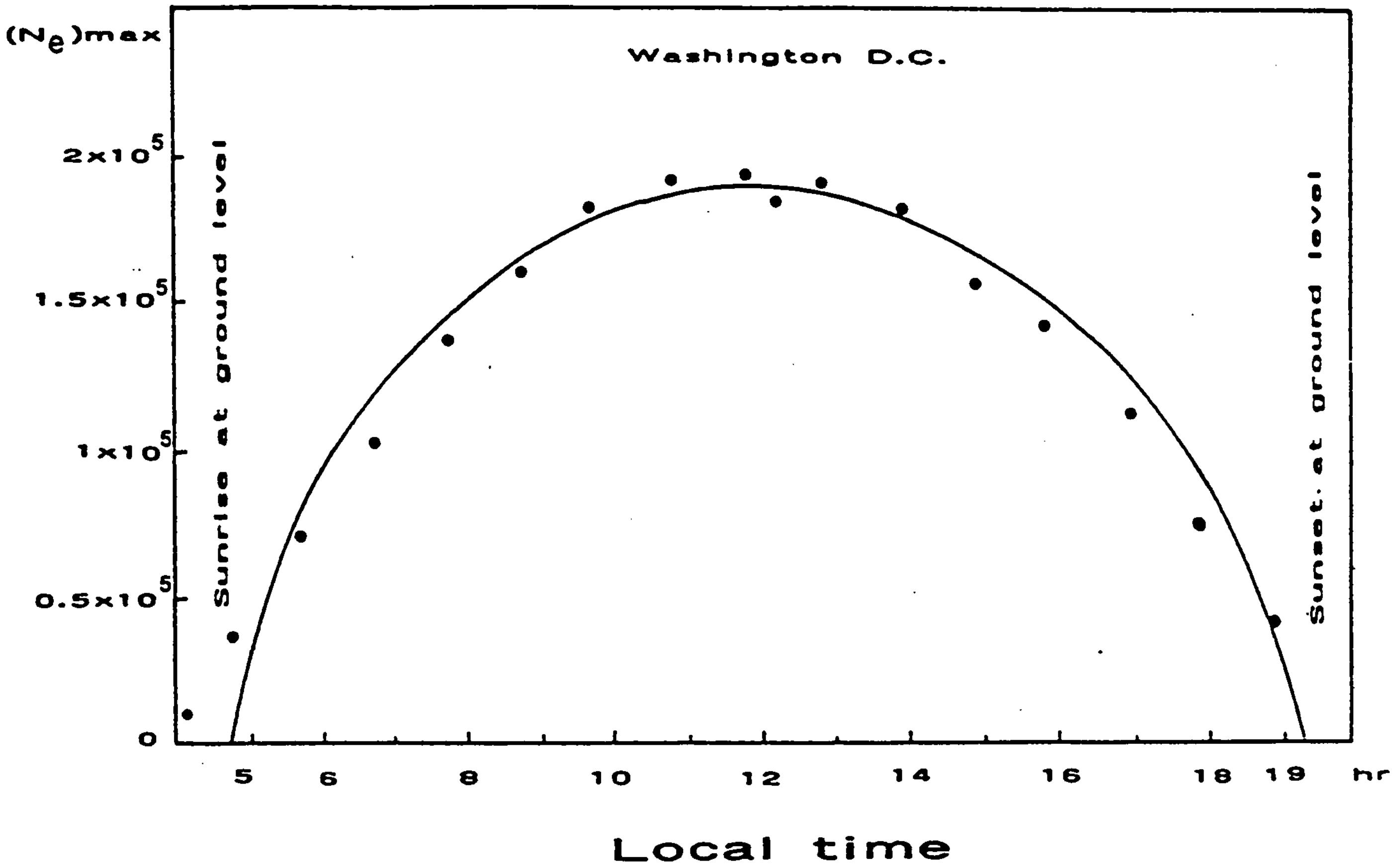

Figure 5b.- Diurnal variation of the maximum electron concentration of the E region at Washington, D.C. during May 1938. The points represent data deduced from observation of critical frequencies (monthly averages), while the curve was traced in accordance with the law $(n_e)_{max} = C(\sin h_\odot)^x$.

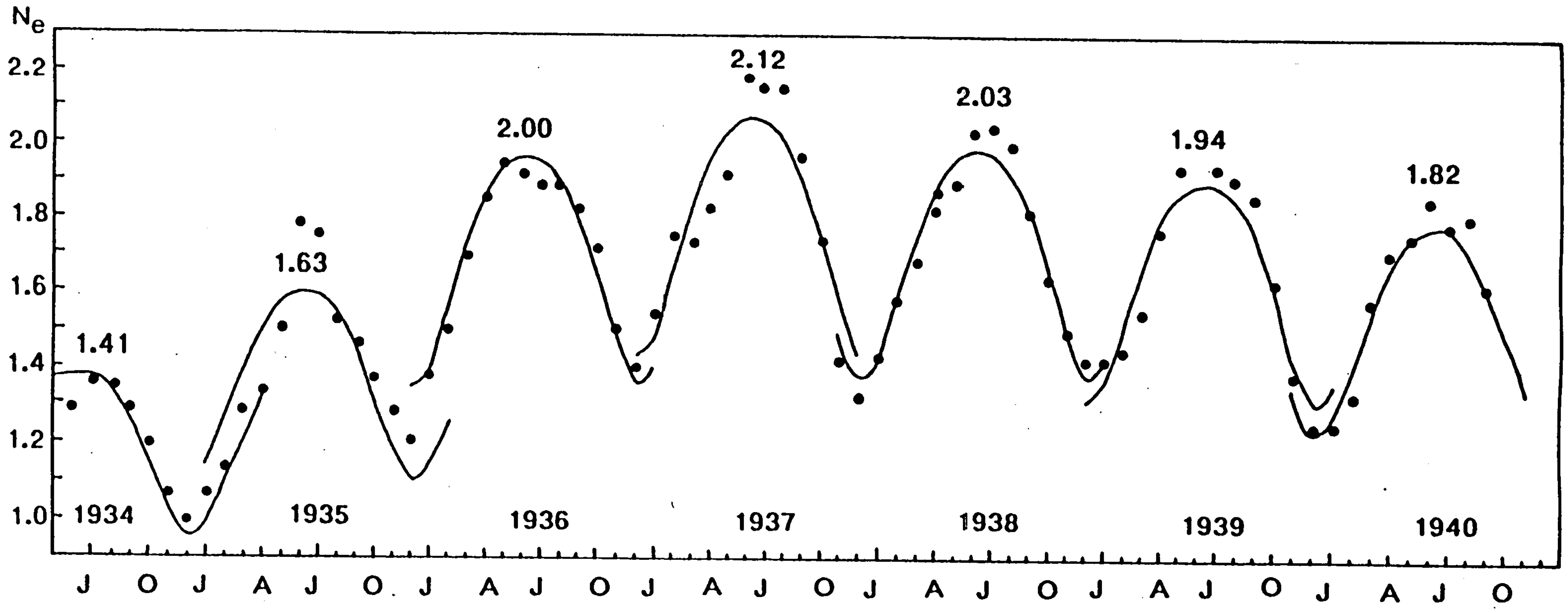

Figure 6.- General variation of the maximum noon electron concentration of the E region at the Washington, D.C. station. The points represent observational average data for each month from 1934 to 1940. The figures above each curve are values for an overhead sun. The 11-year variation is detected by superimposing the long-period variation manifested by the maximum in 1937 on the seasonal variation.

Among the long period variations which had to be expected, attention was focused on the variation resulting from the 11-year solar activity. In figure 6, we have shown the mean monthly value of $(n_e)_{max}$ from 1934 to 1940 at noon, observed at the Washington, D.C., ionospheric station. A simple inspection of the graph showed that a long-period variation was superimposed on the seasonal variation. The former was parallel to the variation of the solar activity, since there was a good correlation between the average ionization and the Wolf sunspot numbers. It was noted, however, that there was no very close relation between the daily variations of the ionization and the number of spots; thus, there was no correspondence whatever between a given spot and the ionization of the E layer.

In figure 7, the data for which simultaneous observations were available for the three stations of Huancayo, Washington, D.C. and Watheroo during the period of January 1939 to June 1940 were also compared in the form of Figure 6. These ionospheric data were also compared with the qualitative data on the facular plages of ionized calcium published in the Quarterly Bulletin of Solar Activity. The fluctuations of the ionospheric results are roughly parallel to those of the arbitrary numbers of the facular plages. In short, a correspondence was found between the solar activity defined by an active index such as the facular plages and certain fluctuations of the maximum electron concentration of the E layer.

Abnormal variations, simple perturbations and ionospheric storms were observed under various forms, but their exact characteristics had not yet been seriously studied in 1939, and had to be determined after World War II.

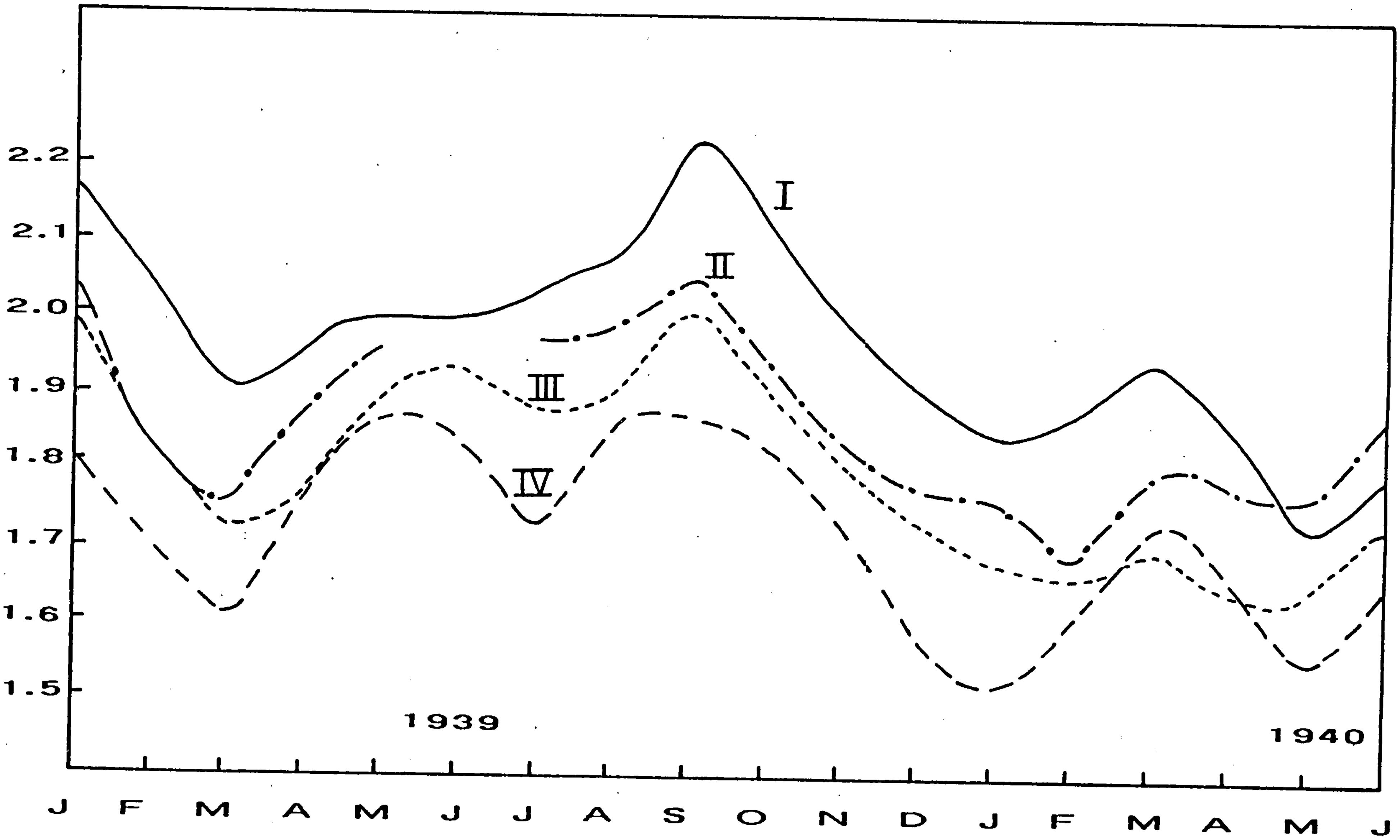

Figure 7.- Effect of solar activity on the state of ionization of the E layer. Curve I, Huancayo, Peru (lat. 12°); curve II, Washington, D.C. (lat. 39°N); curve III, Watheroo, Australia (lat. 30°S); curve IV, square root of arbitrary numbers of facular plages of ionized calcium Ca^+.

The search for the origin of the E layer posed both the problems of absorption of solar energy and of the composition of the upper atmosphere with its vertical distribution and the middle atmosphere, since all the constituents were no longer in molecular form. In particular, it was known (see for example, Götz 1935; Wulf and Deming, 1938; Nicolet, 1939) that the oxygen molecule undergoes a photodissociation in the atmospheric region above 80 km. However, the position of the dissociation maximum of molecular oxygen and, a fortiori, the vertical distribution of atomic and molecular oxygen were not fixed, except on the basis of uncertain hypotheses. Depending on the hypothesis, the dissociation maximum was located at very different altitudes. Since the E region was located in the atmospheric range of 100 to 130 km, the structure of the atmosphere required a sufficiently precise determination. Furthermore, the physical state resulting from the O_2 dissociation gave rise to a series of questions concerning the behavior of the other constituents. A detailed study had indicated that it was possible to arrive at a consistent structure of the upper atmosphere that was radically different from the structure assumed up to 10 years before the prewar time.

The absorption coefficient (Ladenburg and Voorhis, 1933) was determined experimentally with the value $f = 0.193$ for the oscillator strength of the photodissociation continuum beginning at 1750 Å. The corresponding mean value of the absorption cross-section was, therefore, 8.2×10^{-18} cm^2 which corresponds to an absorption peak of about 10^{17} molecules cm^{-2} for the photodissociation of O_2 or 10^{12} cm^{-3} with a scale height of 10 km. Knowledge of recombination to O_2 by a triple collision (see Rabinowitch 1937) and the emission of the forbidden lines of atomic oxygen led to an understanding that the O_2 molecule had its ionospheric action in the formation of the E layer. The absorption cross-section corresponding to the first threshold of the O_2 photodissociation at 1019 Å (Price and Collins, 1935) was considered adequate for the production of the electron concentration of the E layer. There is also a group of preionized bands, but it was shown later than these bands had no practical effect. The spectral range extends from the threshold at 1019 Å to 910 Å, corresponding to the first ionization potential of atomic oxygen with its first computed cross section of 1.4×10^{-17} cm^2 (Bates, 1939).

The diurnal behavior of the ionization state of the F_1 layer was found partly identical to that of the E layer. Indeed, the existence of the F_1 layer was seen at equatorial latitudes throughout the year, whereas at high and middle latitudes, the layer persisted only for heights of the sun of the order of 45°. In other words, the F_1 layer appeared only when its altitude was lowest, and in this case its behavior was analogous to the properties of the E layer : photoionization immediately followed by recombination. The neutral particle density was estimated to be of the order of 3×10^{10} cm^{-3}. But the presence of N_2 with its photoionization at 795 Å (Worley and Jenkins, 1938) was considered as the origin of the F_2 region, even if a firm conclusion in 1939 was far from being understood in the same way in the various analyses. The ionospheric data and the spectroscopic evidence were unreliable. Auroral results supported the view that the temperature was high at great altitude, since the N_2^+ bands were observed by this means at 700-1000 km. But auroras were not associated with normal conditions in the atmosphere, and any information derived from them had to be critically examined. As a typical example, an article by Martyn and Pulley (1936) concluded that the temperatures between the E and F regions were found to reach values of the order of 1000°K from consideration of electron collision frequencies. But the authors claimed that considerable water vapor was present to explain the cooling at night, and that the high temperatures had to be attributed mainly to the absorption of solar ultraviolet radiation by ozone present at these high altitudes. Furthermore, the electron concentrations were found to correlate directly with the barometric pressure at the ground. In addition, the seasonal and diurnal variations of the green line intensity were considered subject to similar variations of electron density in the F_2 region. It followed from these considerations above that the ionization of the F_2 region presented irregularities which observation was not able to follow. Whereas the virtual heights of the ionization peaks of the E layer corresponded fairly well to the real heights (thin layer), this was no longer the case of those of the F_2 region, which were strongly influenced by the effect of the lower layers (absorption). In fact, the variations of the virtual heights of the F_2 region did not correspond to the variations of the actual heights, i.e., the altitudes of the maximum of the electron concentration. Figures 8 and 9 were typical examples of different variations. Whereas the altitudes of the E and F_1 diminished under the solar influence, the F_2 region showed rather an inverse variation with the virtual height. In addition, the latitude effect also appeared to follow this tendency; observations made at Huancayo, Watheroo and Washington, D.C. tended to show that the altitude of the ionization peak at Huancayo (Equator) was definitely greater than the respective altitudes at Watheroo (Australia) and Washington, D.C. But since the results published on the real heights were incomplete and generally in mutual disagreement, it was not possible to carry out a more extensive examination. Nevertheless, a conclusion was adopted about the recombination in the F_2 layer : to assume a law

$$dn_e/dt = \text{photodissociation} - \text{recombination} \equiv \beta n_e$$

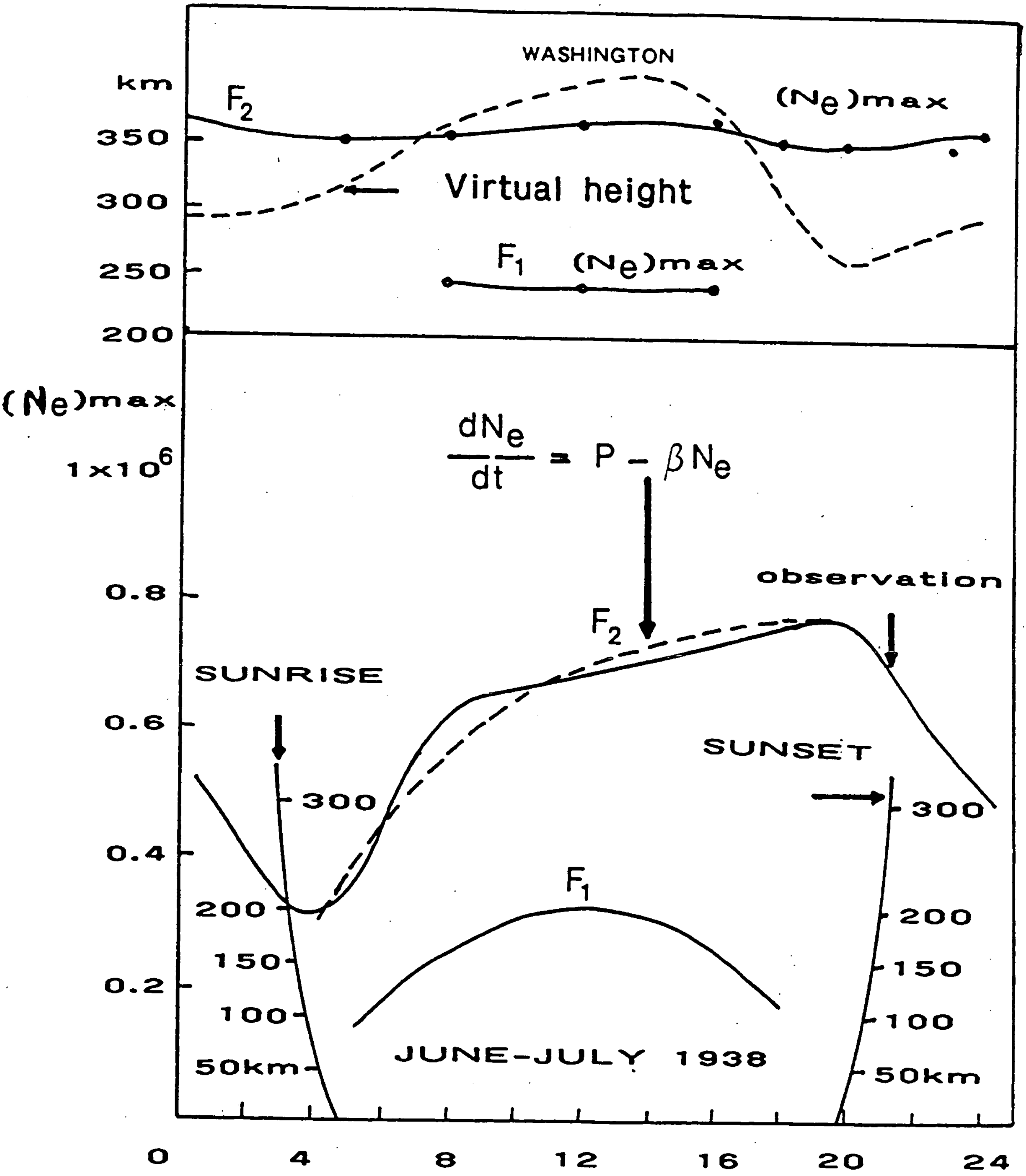

Figure 8.- Values of the maximum electron concentration and of its altitude in the F_1 and F_2 regions at Washington, D.C. in June-July 1938 (Summer) according to F.L. Mohler (1940).

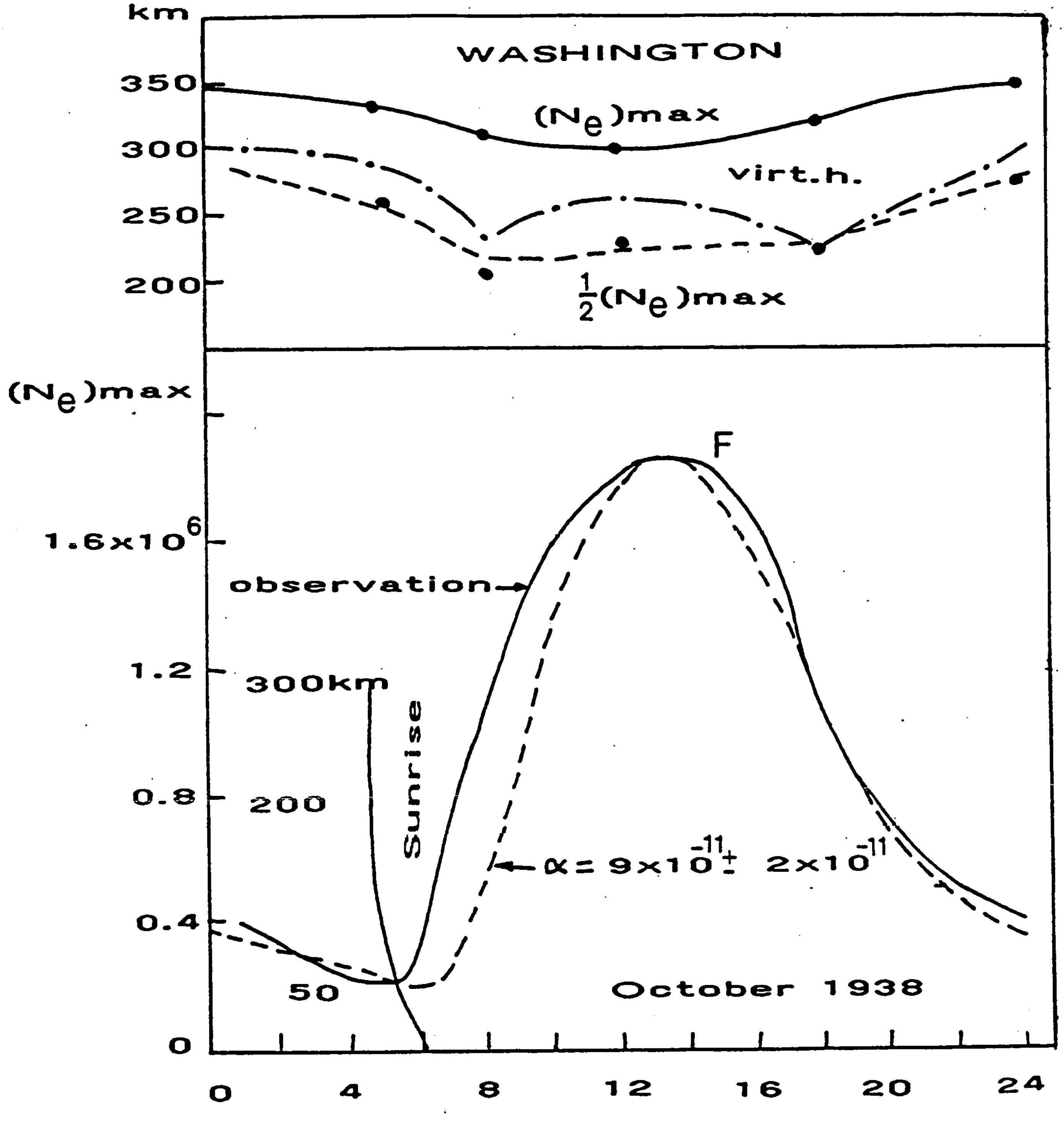

Figure 9.- Values of the maximum electron concentration of the F2 region and of its altitude at Washington, D.C. in October 1938 (Autumn) according to F.L. Mohler, Jour. Res. Nat. Bur. Stand., 25, 507-518, 1940.

as the characteristic variation of the ionization of the F2 region. There was no photoionization equilibrium. During World War II (1939-1945) the ionospheric chronology was stopped, but, on the other hand, in order to serve the operational requirements, many new ionospheric stations were established over the Globe. The detailed radio character figures were known only several years later. On the other hand, experimental A-4 rockets (later called V-2) were test-fired in Germany in May 1943. A lot of them were sent to White Sands, New Mexico in 1945 and it became possible to test the structure of the upper atmosphere.

5. Before the beginning of the analysis of scientific results obtained by rockets

The processes for understanding the structure of the upper atmosphere which were used before World War II became generally obsolete when the V2 rockets yielded their first successful results. In July 1948, 21 succesful flights on 31 V2 rockets fired from White Sands since 1946 gave scientific results at various heights ranging from 100 to 185 km. Very few scientific concepts were introduced at the first international meetings held between 1946 and 1948. Nevertheless, the URSI general assembly, held in Paris in 1946, indicated a few new aspects in the ionospheric structure. The meeting in 1947 of the Physical Society of the Gassiot Committee in London organized by Bates and Massey (1948) discussed the emission spectra of the night sky and aurora. The 25 papers gave a broad view of the state of knowledge as it was before 1940 (complexity of the problems involved and observations in serious disagreement) in spite of the amount of work done through 1947. In 1947, a meeting in Lyon was organized by J. Dufay on the "Relations entre les phénomènes solaires et terrestres". All possibilities concerning the relationships between solar and geophysical phenomena were referred or discussed in 40 papers with various multiple conclusions, because a general confrontation of issues had not yet been possible. The general assembly of the International Union of Geodesy and Geophysics, held in Oslo in 1948, was immediately followed by the general assembly of the International Astronomical Union in Zurich. The Transactions of the Oslo Meeting, August 19-28, 1948 of the Association of Terrestrial Magnetism and Electricity, IATME Bulletin No 13, Washington 1950, edited by J.W. Joyce (1950), gave a description (568 pages) for each country of the various results which were obtained from 1939 to 1948. As a typical example, Gartlein (1950) demonstrated that the Balmer lines of atomic hydrogen in several auroras were broad, indicating an influx of hydrogen appearing during sudden outbursts of the aurora. In addition, Nicolet (1950) reported that in a spectrum obtained by Störmer (March 29, 1940) the hydrogen lines were only present in the southern part of an auroral arc during 20 minutes at 23h. Furthermore, in cloudlike auroras (3 January, 1940) at about 105 km in a thickness of 10-20 km the velocities were between 700 and 800 m/sec. In addition, the radio waves emissions detected by radar during World War II (see detailed references Reber and Greenstein (1947) were a substantial contribution for advances in aeronomy, particularly the microwave solar radiation. A complete description was given by Nicolet (1949) in "Bruits solaires et cosmiques" . Figures 10, 11 and 12 are a typical descriptive representation of the emission of a quiet sun in the metric, decimetric and centimetric spectral regions, respectively. They show the kind of roles that the photosphere, chromosphere and corona can play in the various spectral ranges. It was found, however, that the propagation of these solar emissions depended also on various other conditions such as the effect of the refractive index, the variation of temperatures, the detailed structure of the solar atmosphere, and the solar activity.

After World War II, The Commission for the Study of the Relationships between the Solar and Terrestrial Phenomena published a report on the scientific results obtained between 1939 and 1946. Such a report (Report VI) serves as a bibliographic report of the various studies conducted during the war period.

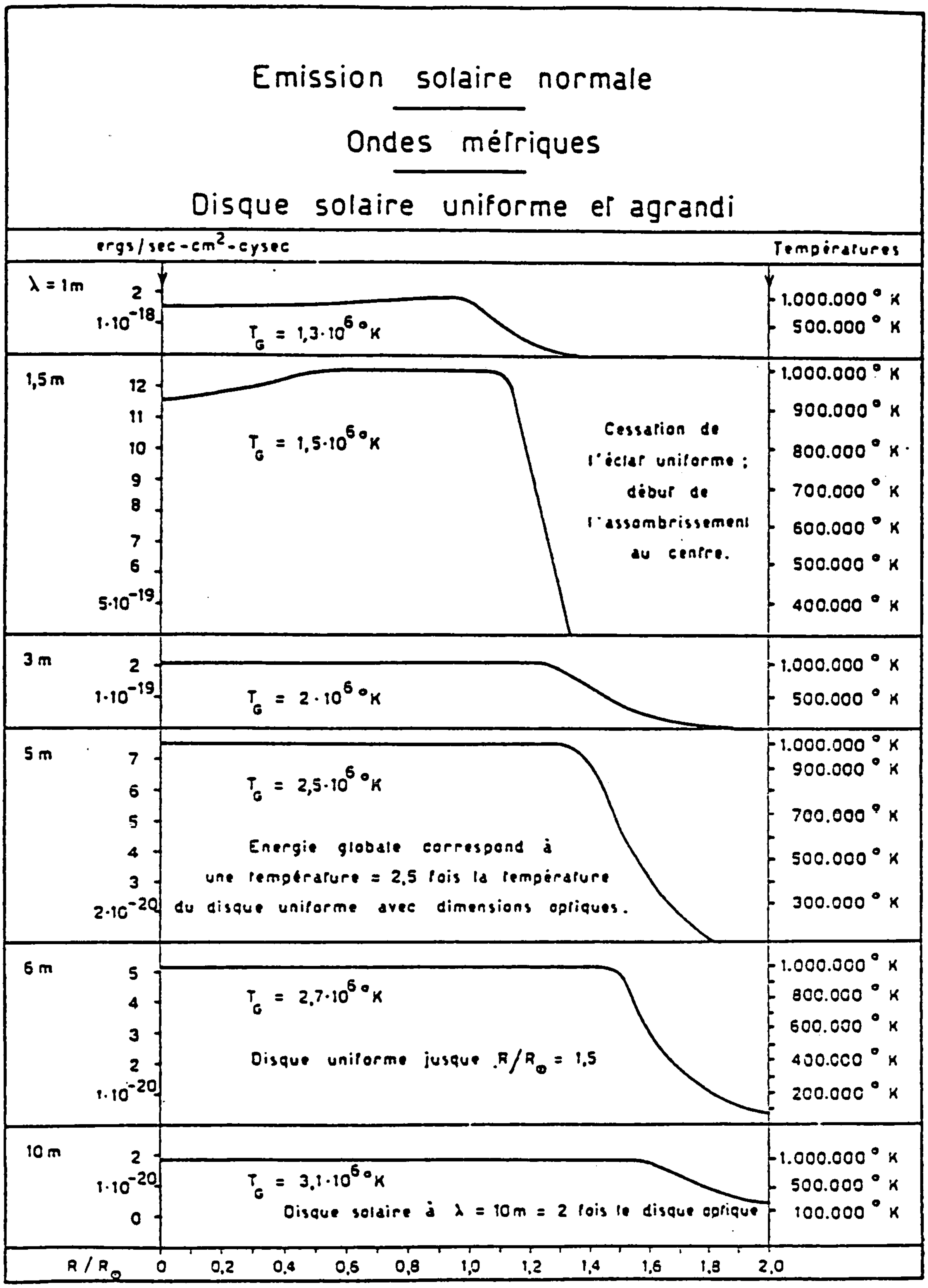

Fig. 10 — Aspect du Soleil quiet dans le domaine des ondes métriques.

Cet aspect résulte d'un schéma particulier : couronne à symétrie radiale de température électronique égale à 10^6 °K et chromosphère de température égale à 10.000°K. Le calcul de l'émission a été effectué sans tenir compte du fait que le milieu présente un indice de réfraction $\mu < 1$ et pouvant devenir nul pour certaines longueurs d'onde.

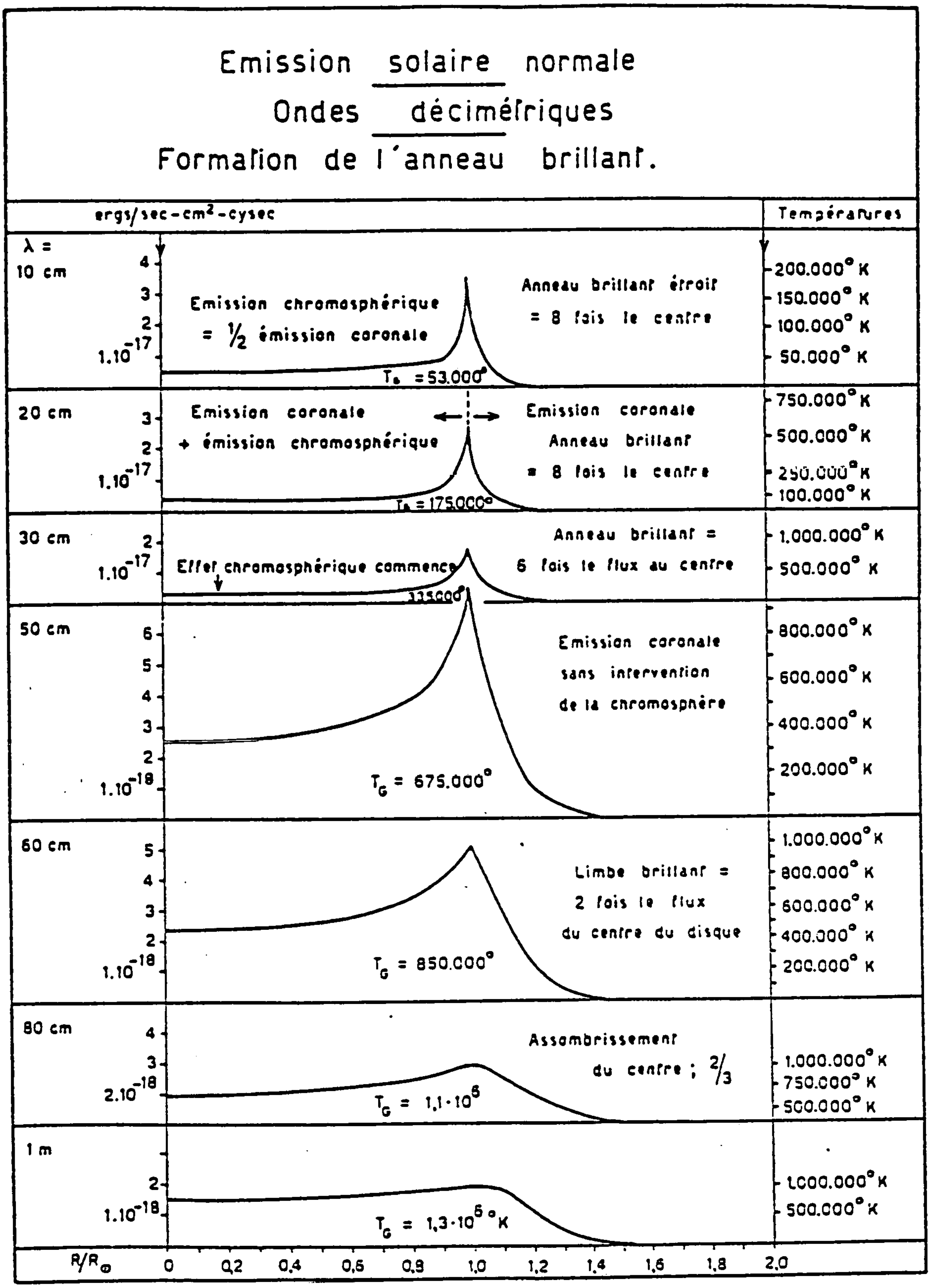

Figure 11.- Aspect du Soleil quiet dans le domaine des ondes décimétriques où on n'a pas considéré l'effet du milieu d'indice $0 < \mu < 1$ sur la propagation et l'émission des ondes. En d'autres termes, les épaisseurs optiques ont été définies pour un milieu d'indice $\mu = 1$.

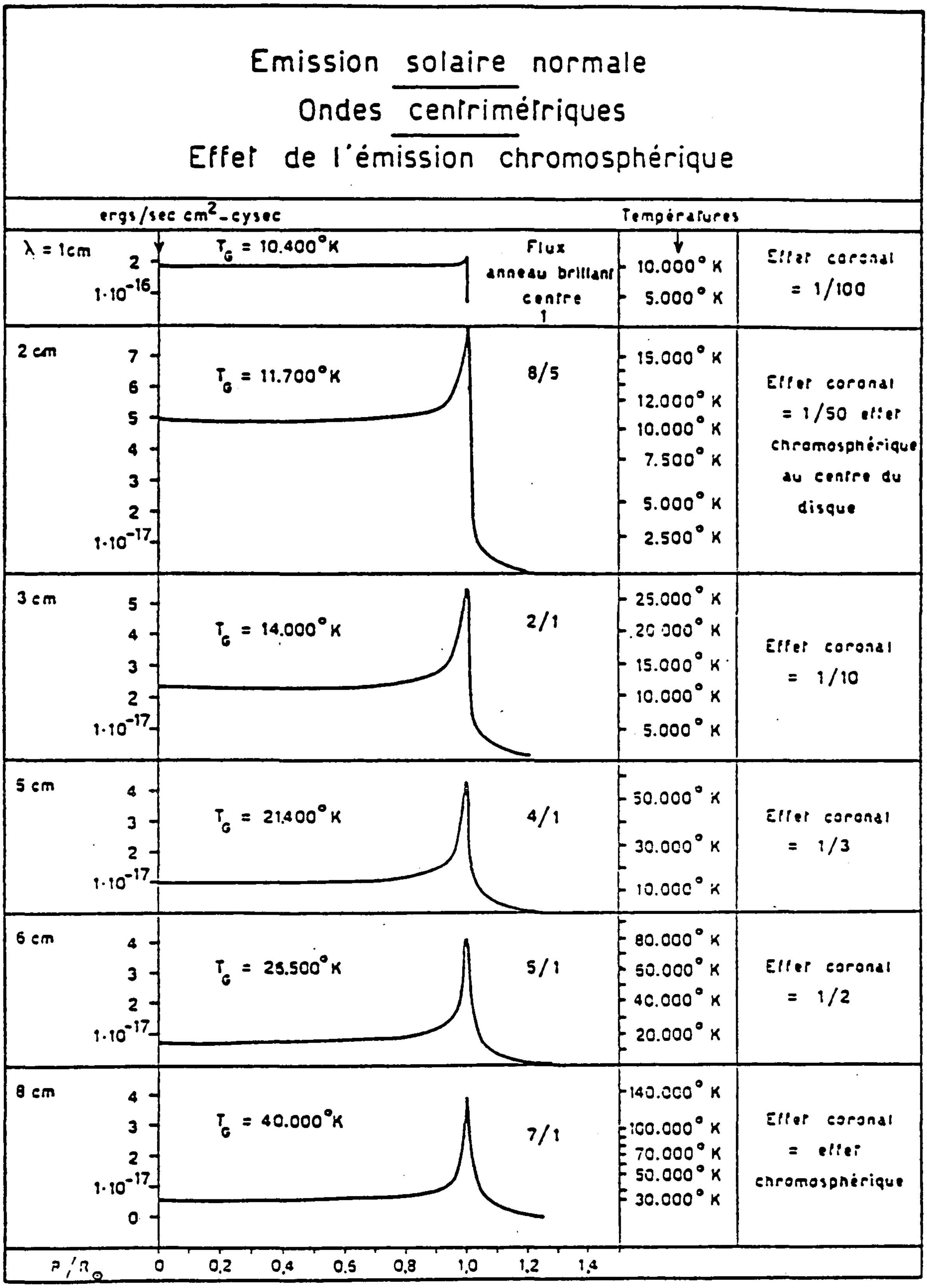

Fig. 12.- - Aspect du Soleil quiet dans le domaine des ondes centimétriques.

Le calcul est basé sur une détermination des épaisseurs optiques pour une température électronique dans la chromosphère de 10.000°K.

Les observateurs devraient déterminer si possible la variation du flux en allant du centre au bord. Avec la détermination du flux global, on obtiendrait des indications très utiles pour l'étude théorique précise. Dans ce domaine de longueurs d'onde, l'influence du milieu d'indice $\mu < 1$ diminue par rapport à l'effet signalé dans les ondes métriques et décimétriques.

6. A new step forward

In 1950, Barbier, Bates and Nicolet were invited by Frank Roach at Pasadena to study the problems of the airglow (new word introduced by Elvey instead of "nightsky"). Chapman was also present at CalTec. Immediately, Bates and Nicolet (1950) in a paper entitled "Theoretical considerations regarding the altitude of the layer responsible for the nocturnal emission of the sodium D lines" reached the conclusion that the luminous layer was low, below 100 km. But the main interest was the observation at McDonald Observatory, by Elvey and Roach, at low altitude (also below 100 km) of a strong infrared emission, that was related to the discovery by Meinel (1950a, b) at Yerkes Observatory of the rotation vibration bands of the OH molecule. Thanks to the observational data (not yet published) of the Naval Research Laboratory sent by R. Tousey (letter of 7 April 1950) the vertical distribution of ozone up to an altitude of 70 km was measured on June 14, 1949 at sunset; the number of molecules per cm^3 was 5.6×10^{10} at 50 km, 8×10^9 at 60 km and 6.5×10^8 at 70 km. In the same letter, the solar radiation near Lyman-α based on incompletely calibrated data was given as corresponding to a black-body near 5000°K instead of 6000°K.

With these observational data a theoretical analysis was made on the origin of the OH rotation-vibration bands in the airglow. After a short consideration of the problem of atmospheric hydrogen (Bates and Nicolet, 1950b) a detailed analysis (Bates and Nicolet, 1950c; 1950d) yielded the conclusion that among the various possible processes (triple collision, radiative formation, ...) the process

$$H + O_3 \rightarrow O_2 + OH\ ({}^3\Pi_{v \leq 9})$$

corresponded to the observations made by Meinel (1950). This indicated that the emission to vibrational rotational bands of the hydroxyl radical was limited to $v \leq 9$. It was, therefore, demonstrated that the concentration of hydrogen atoms in the neighborhood of the 100 km level was of the order of 10^8 to 10^9 per cm^3, where the total particle concentration was considered to be of the order of 10^{13} per cm^3. A final analysis led to the problems of the hydrogen escape and replenishment from the lower atmosphere. Roach, Pettit and Williams (1950) used the van Rhijn technique to determine the altitude of the emission layer. They found it to be 70 ± 20 km, which is consistent with the theoretical prediction.

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First report - Premier Rapport, 202 pages, 1926

Contents - Table des matières

Second Report - Deuxième Rapport, 131 pages, 1929.

Contents - Table des matières

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(Results from 1939 tp 1946)

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THE AIRGLOW SPECTRUM

BY

A.L. BROADFOOT AND K.R. KENDALL

FROM

J. GEOPHYS. RES.

72, 426-428, 1968

IDENTIFICATIONS TAKEN

FROM CHAMBERLAIN (1961)

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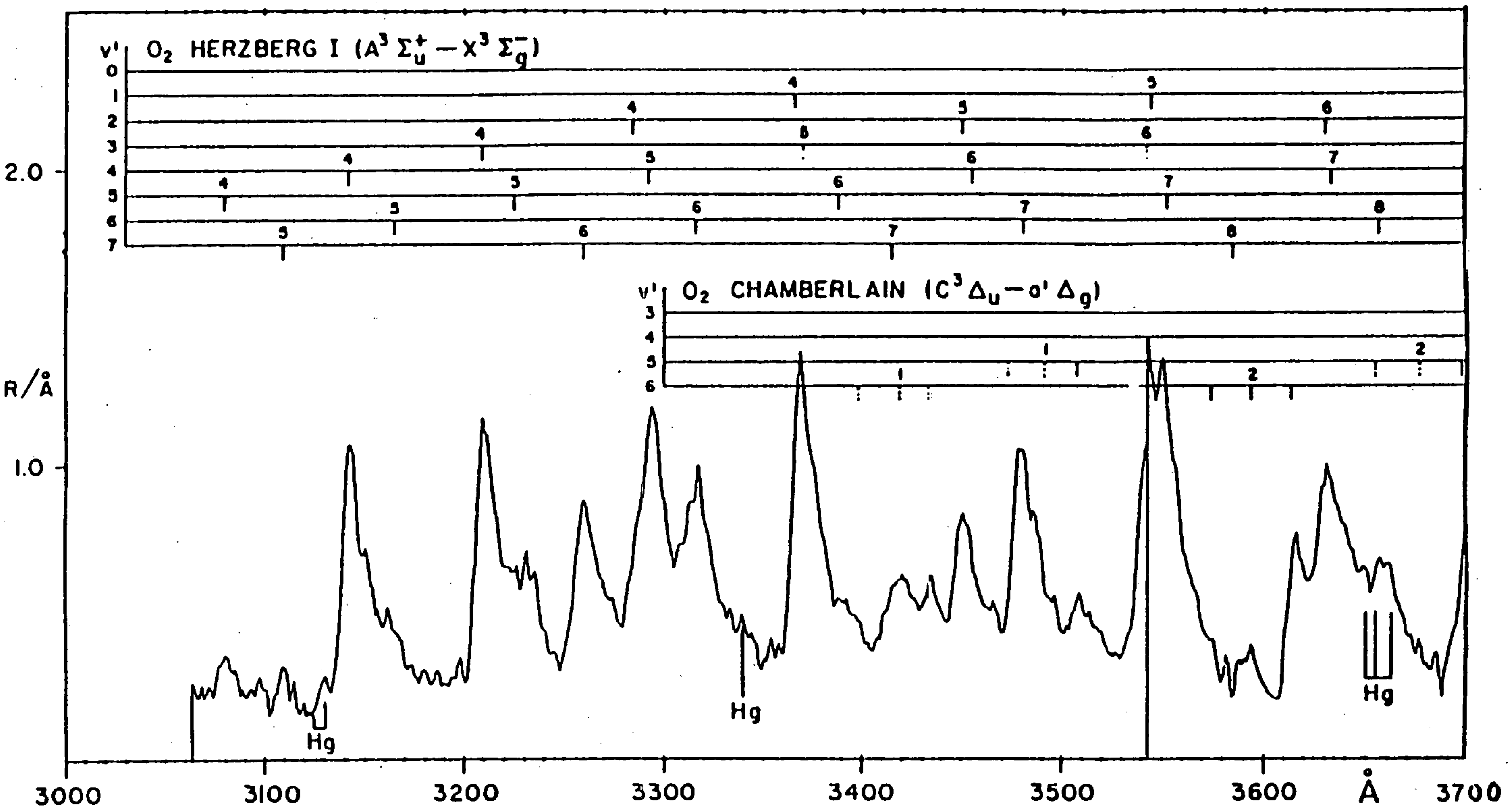
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v'
0
1
2
3
4
5
6
7
O_2 CHAMBERLAIN $(C^3\Delta_u - a'\Delta_g)$
v'
3
4
5
6
1
2
R/Å
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1.0
Hg
Hg
Hg
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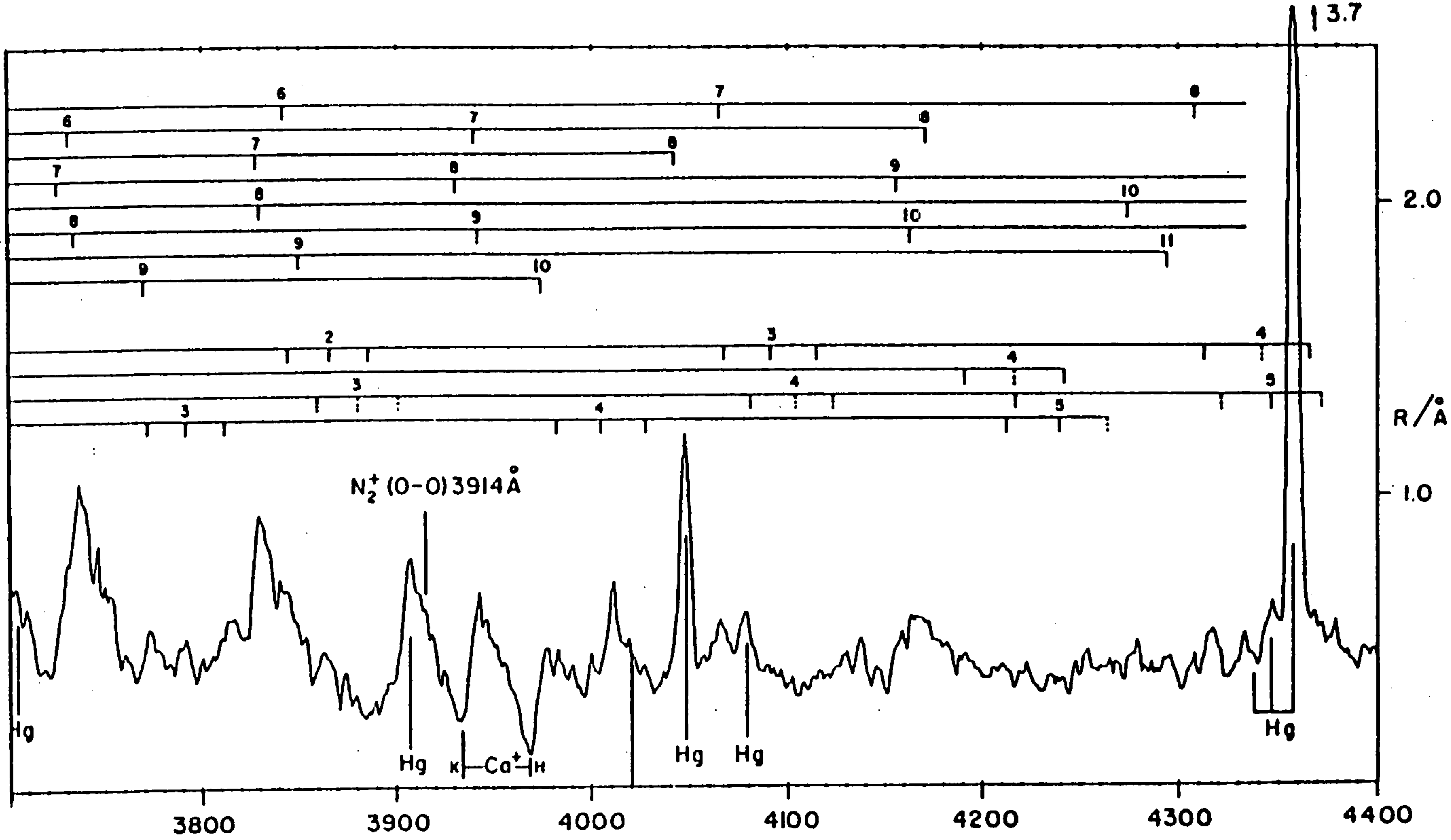
3100
3200
3300
3400
3500
3600
Å
3700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R/Å
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Hg
Hg
K
Ca$^+$
H
Hg
Hg
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3800
3900
4000
4100
4200
4300
4400
6
7
8
6
7
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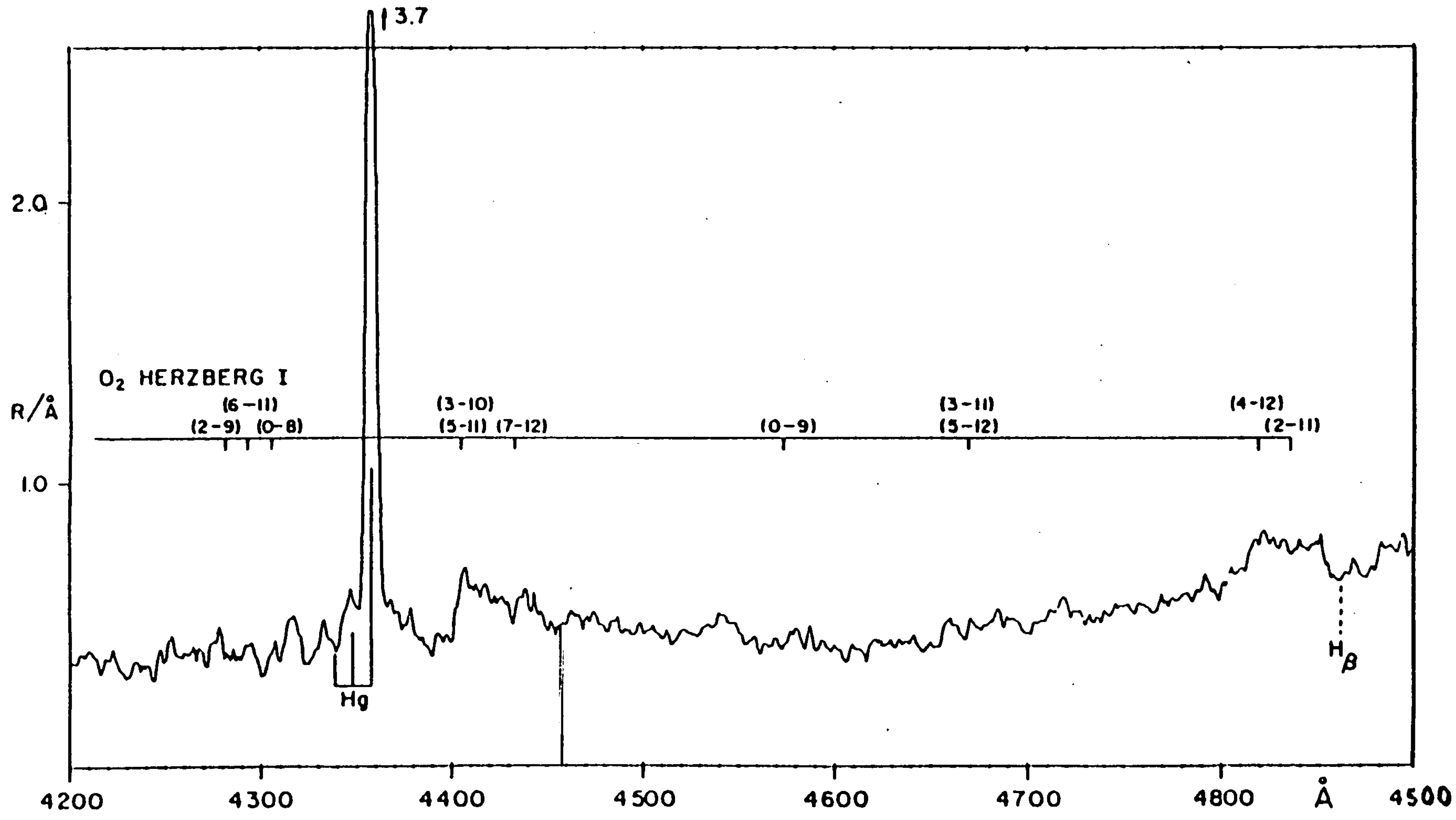
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R/Å
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(2-9)
(0-8)
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(5-11)
(7-12)
(0-9)
(3-11)
(5-12)
(4-12)
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Hg
H$_\beta$
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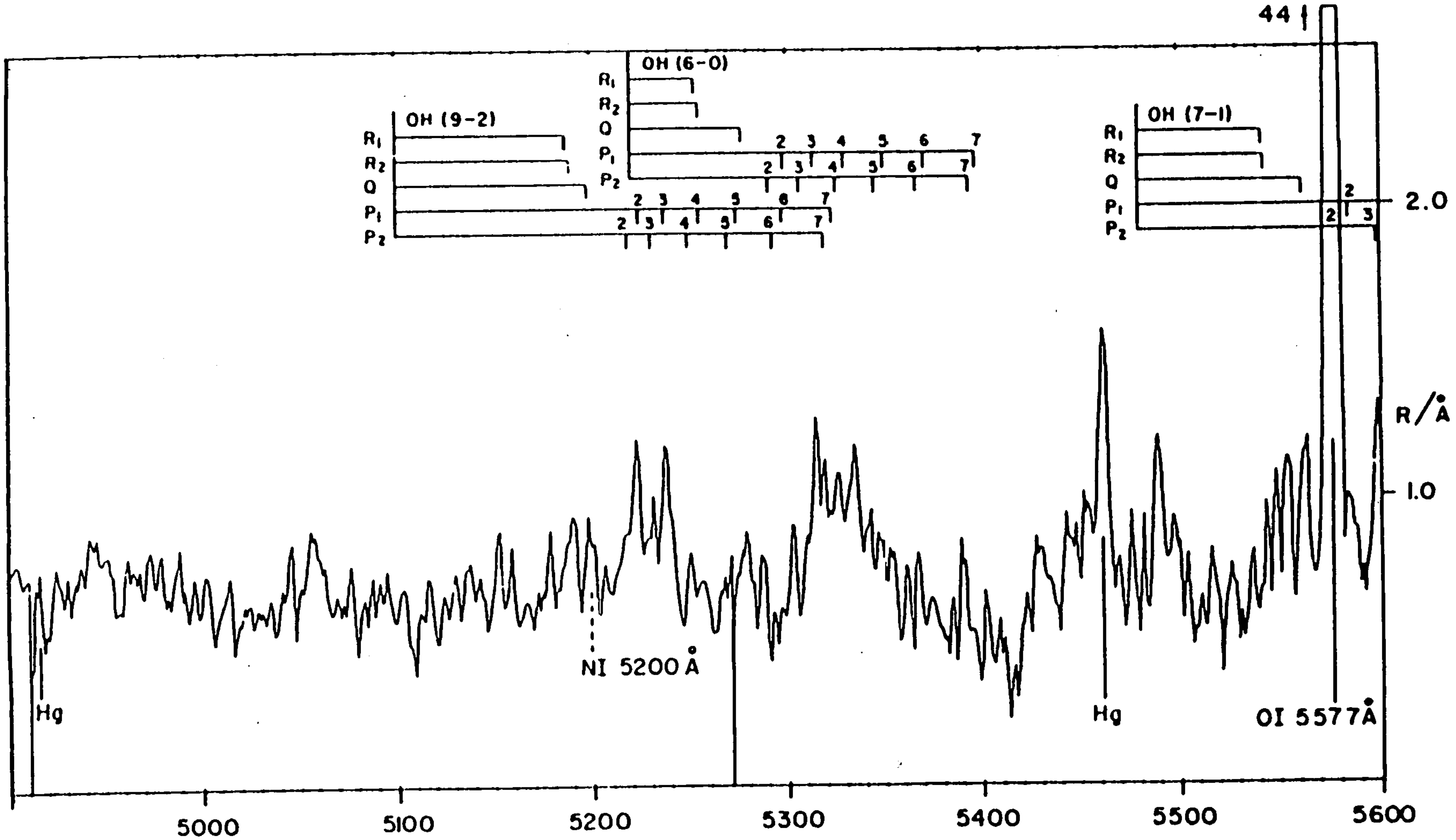
4400
4500
4600
4700
4800
Å
4500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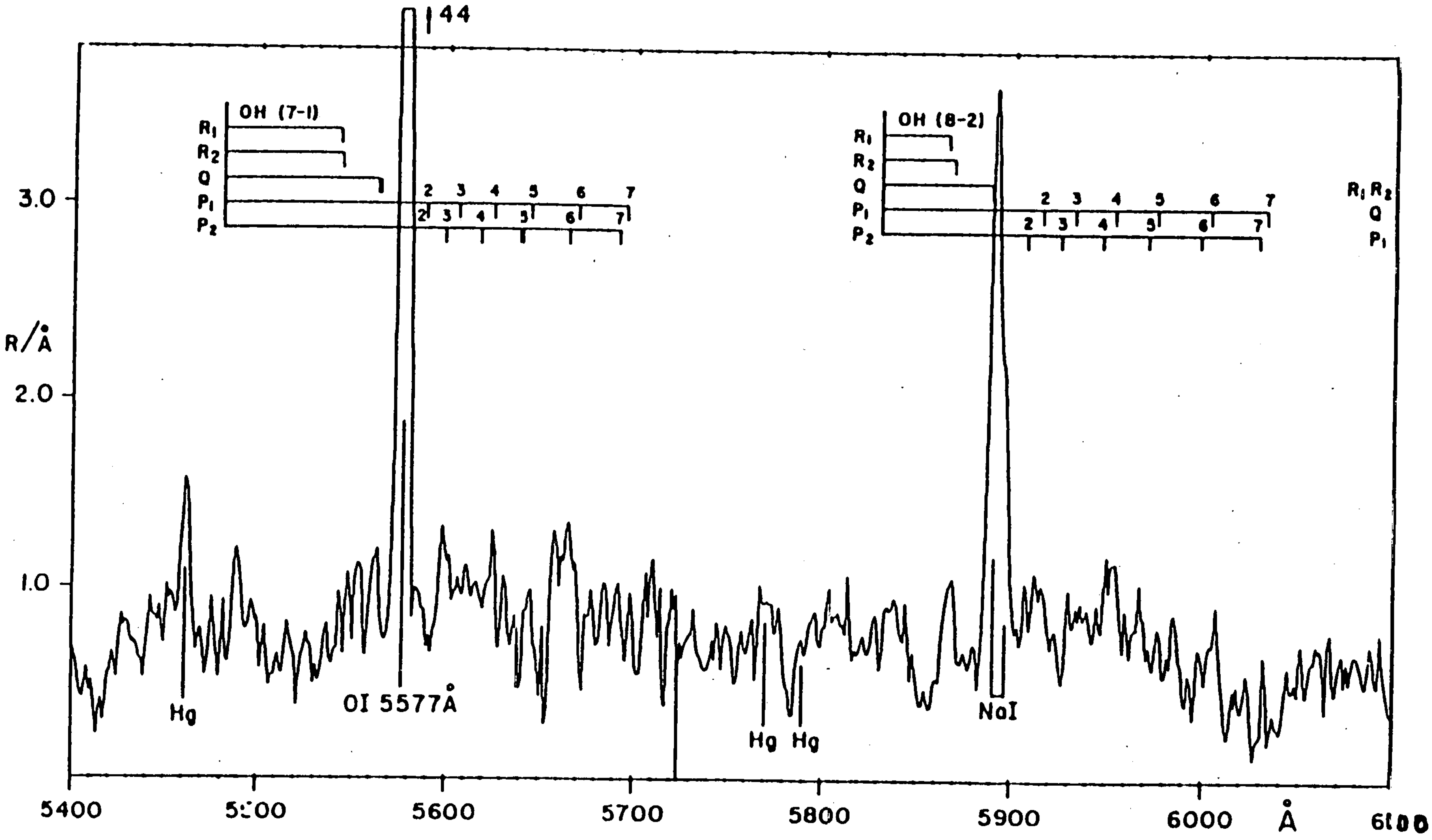
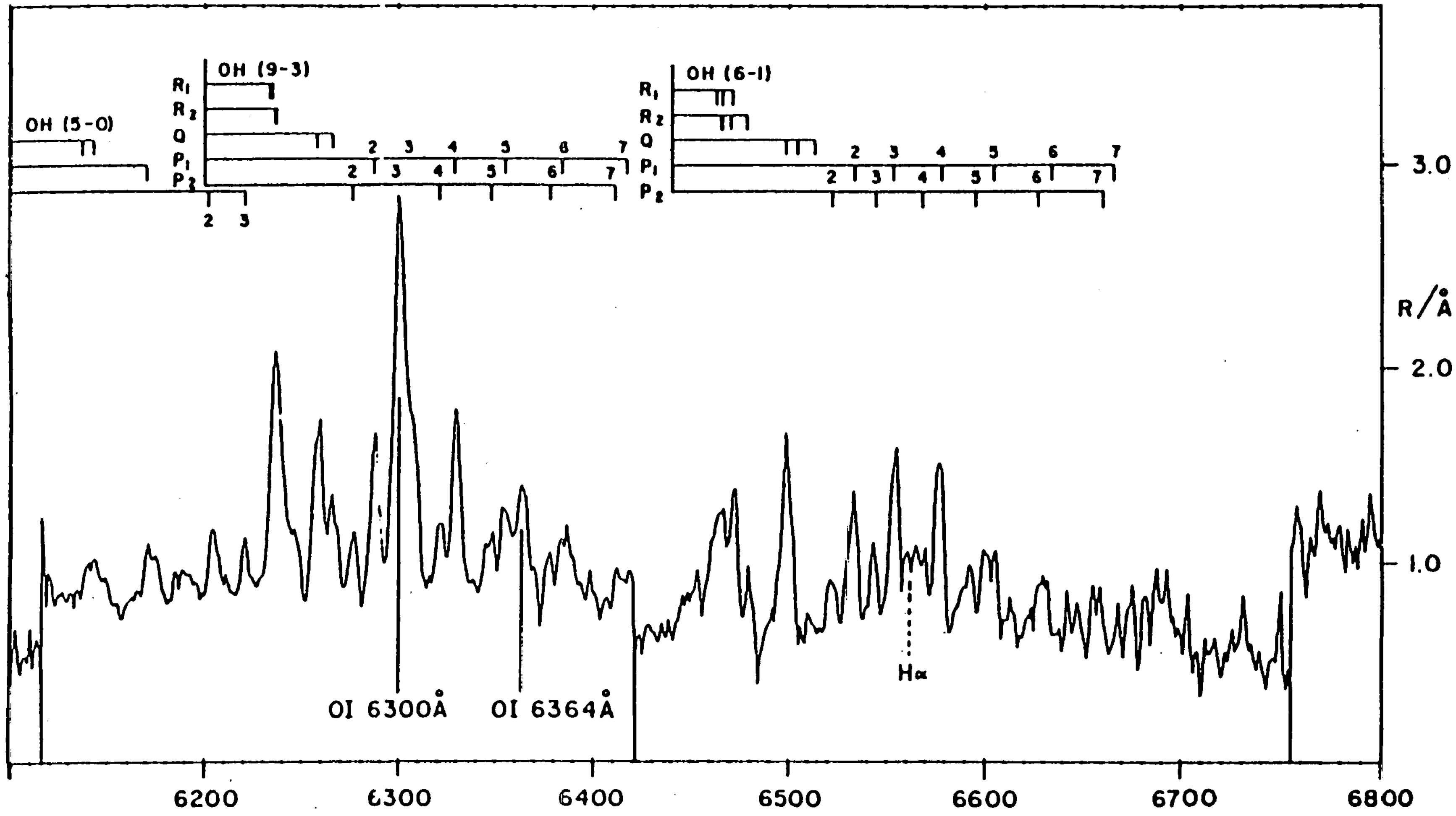
R₁
R₂
Q
P₁
P₂
2 3 4 5 6 7
2 3 4 5 6 7
OH (6-0)
R₁
R₂
Q
P₁
P₂
2 3 4 5 6 7
2 3 4 5 6 7
OH (7-1)
R₁
R₂
Q
P₁
P₂
2
2 3
2.0
R/Å
1.0
Hg
NI 5200 Å
Hg
OI 5577Å
5000
5100
5200
5300
5400
5500
5600


44
OH (7-1)
R₁
R₂
Q
P₁
P₂
2 3 4 5 6 7
2 3 4 5 6 7
OH (8-2)
R₁
R₂
Q
P₁
P₂
2 3 4 5 6 7
2 3 4 5 6 7
R₁ R₂
Q
P₁
3.0
2.0
1.0
R/Å
Hg
OI 5577Å
Hg
Hg
NaI
5400
5500
5600
5700
5800
5900
6000
Å
6100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OH (9-3)
OH (6-1)
R₁
R₂
Q
P₁
P₂
2 3 4 5 6 7
OI 6300Å
OI 6364Å
Hα
R/Å
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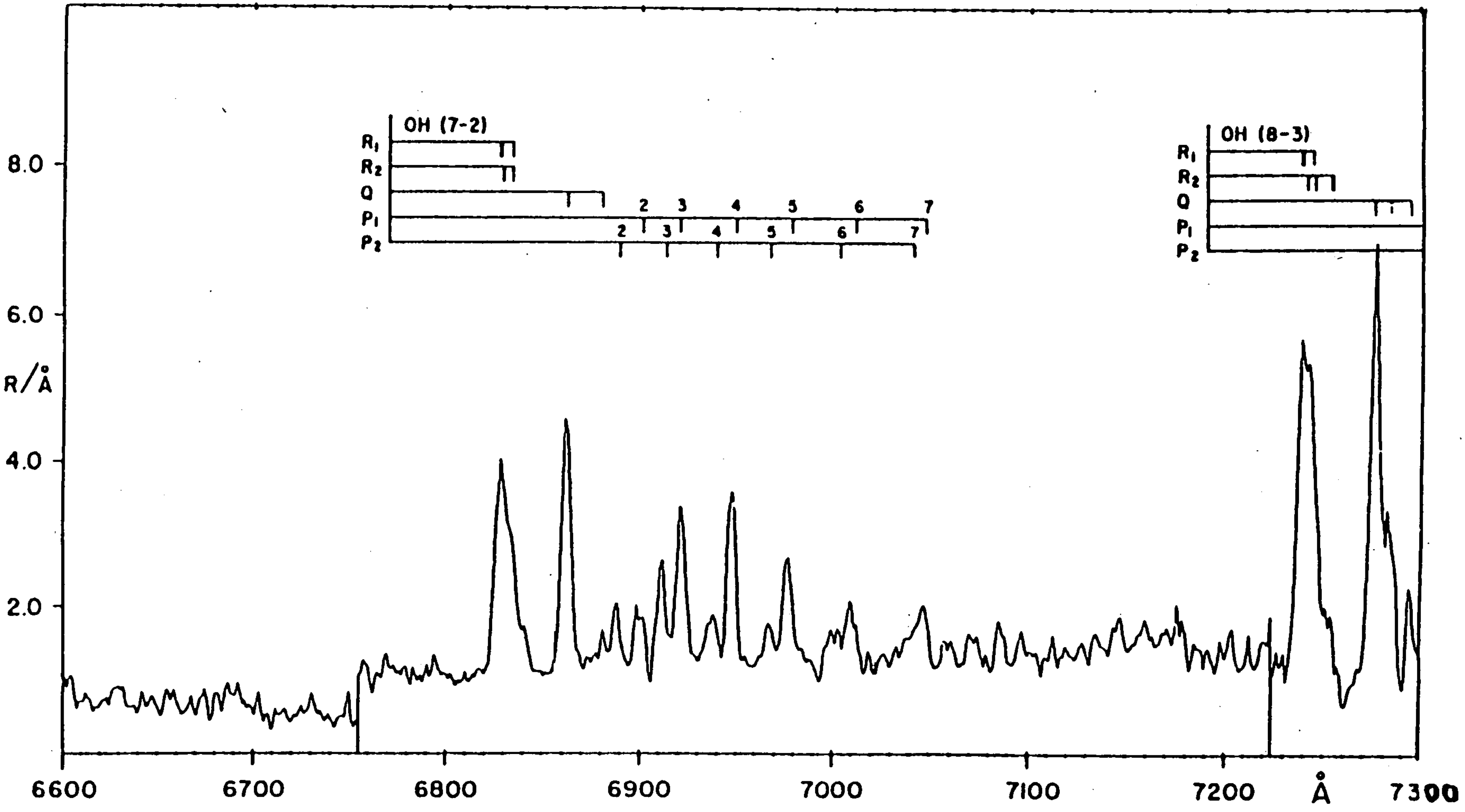
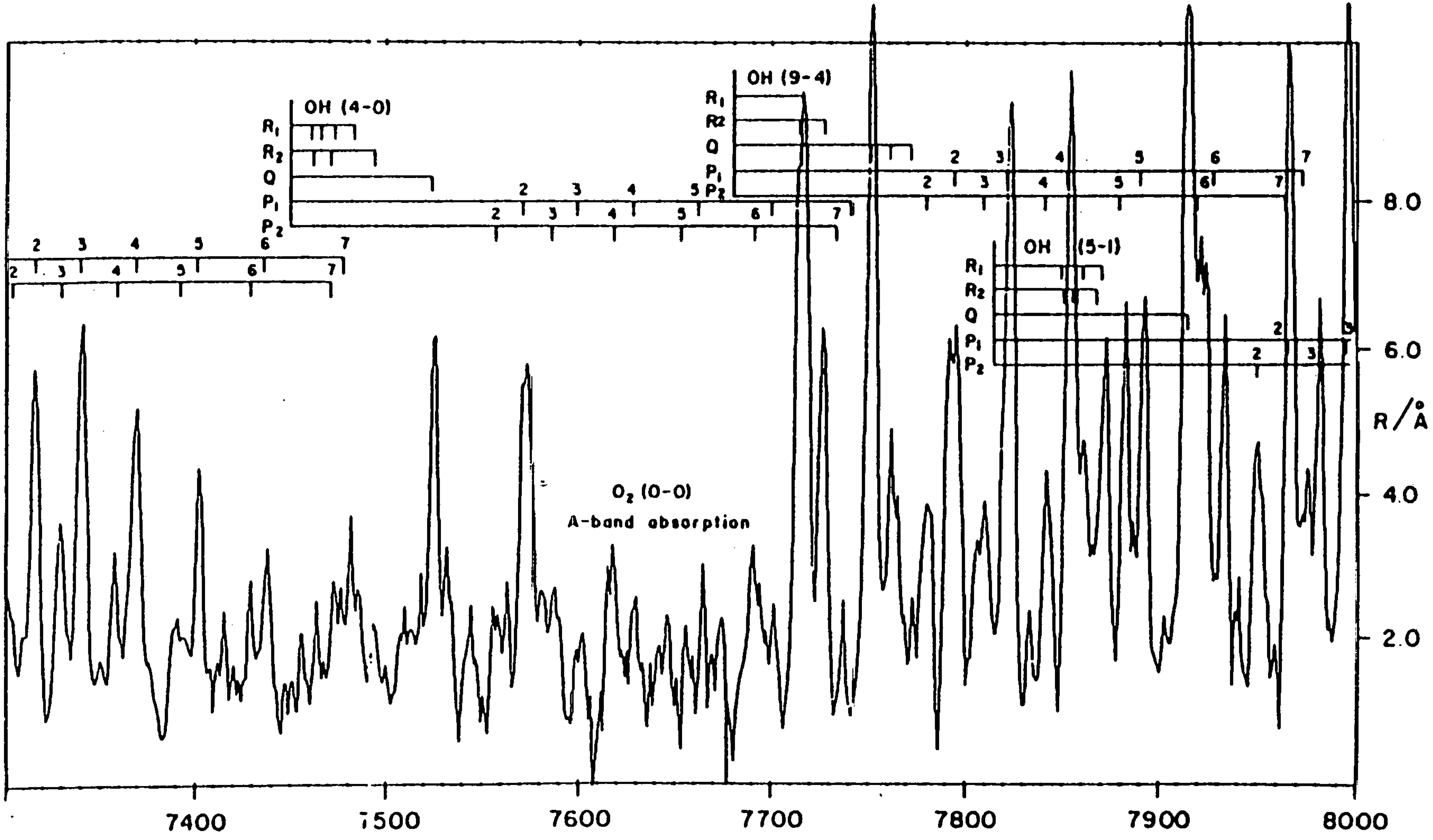
2.0
1.0
6200
6300
6400
6500
6600
6700
6800


OH (7-2)
R₁
R₂
Q
P₁
P₂
2
3
4
5
6
7
2
3
4
5
6
7
OH (8-3)
R₁
R₂
Q
P₁
P₂
8.0
6.0
R/Å
4.0
2.0
6600
6700
6800
6900
7000
7100
7200
Å
7300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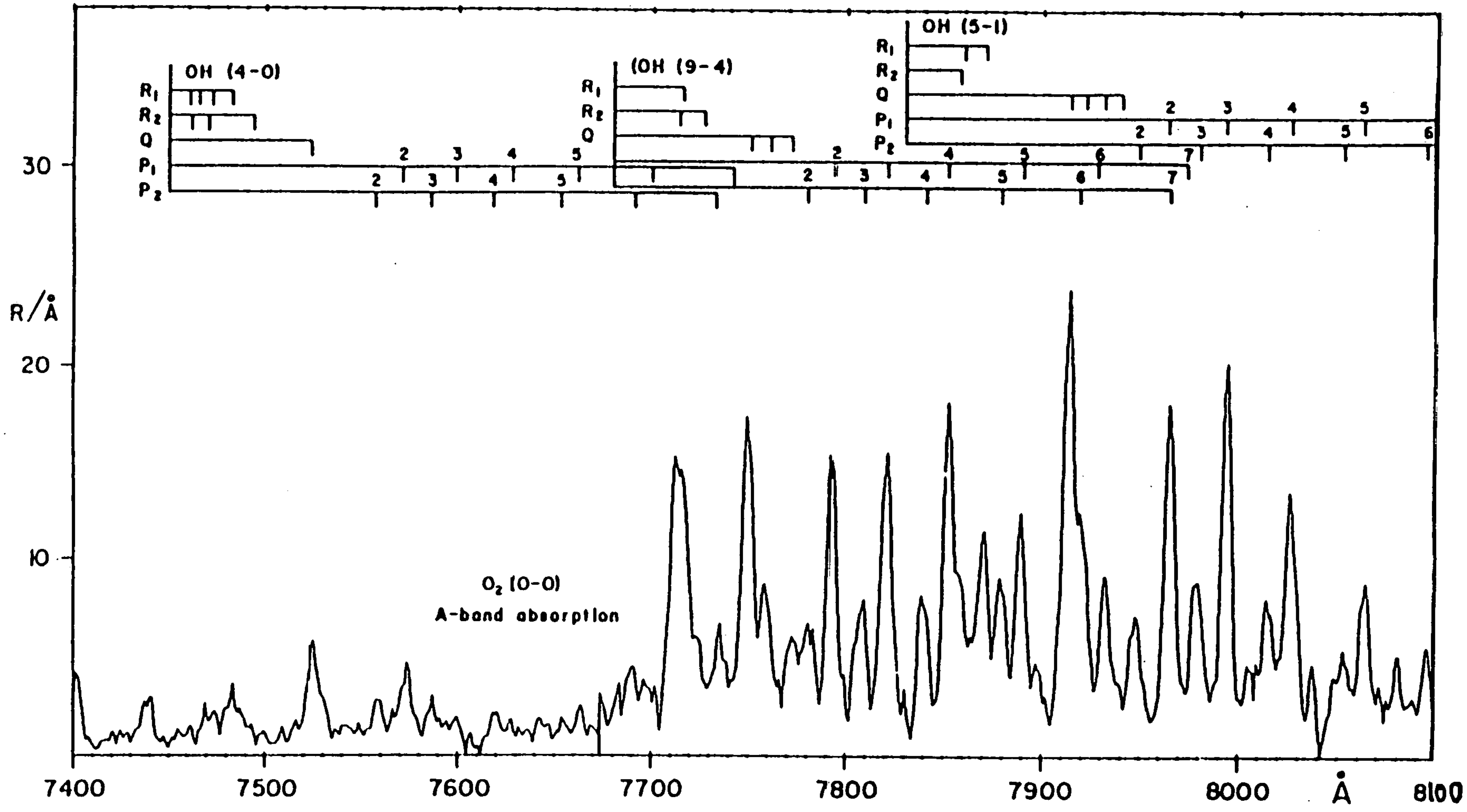
R₂
Q
P₁
P₂
OH (9-4)
R₁
R2
Q
P₁
P₂
OH (5-1)
R₁
R₂
Q
P₁
P₂
2
3
4
5
6
7
O₂ (0-0)
A-band absorption
8.0
6.0
4.0
2.0
R/Å
7400
7500
7600
7700
7800
7900
8000


OH (4-0)
(OH (9-4)
OH (5-1)
R₁
R₂
Q
P₁
P₂
2
3
4
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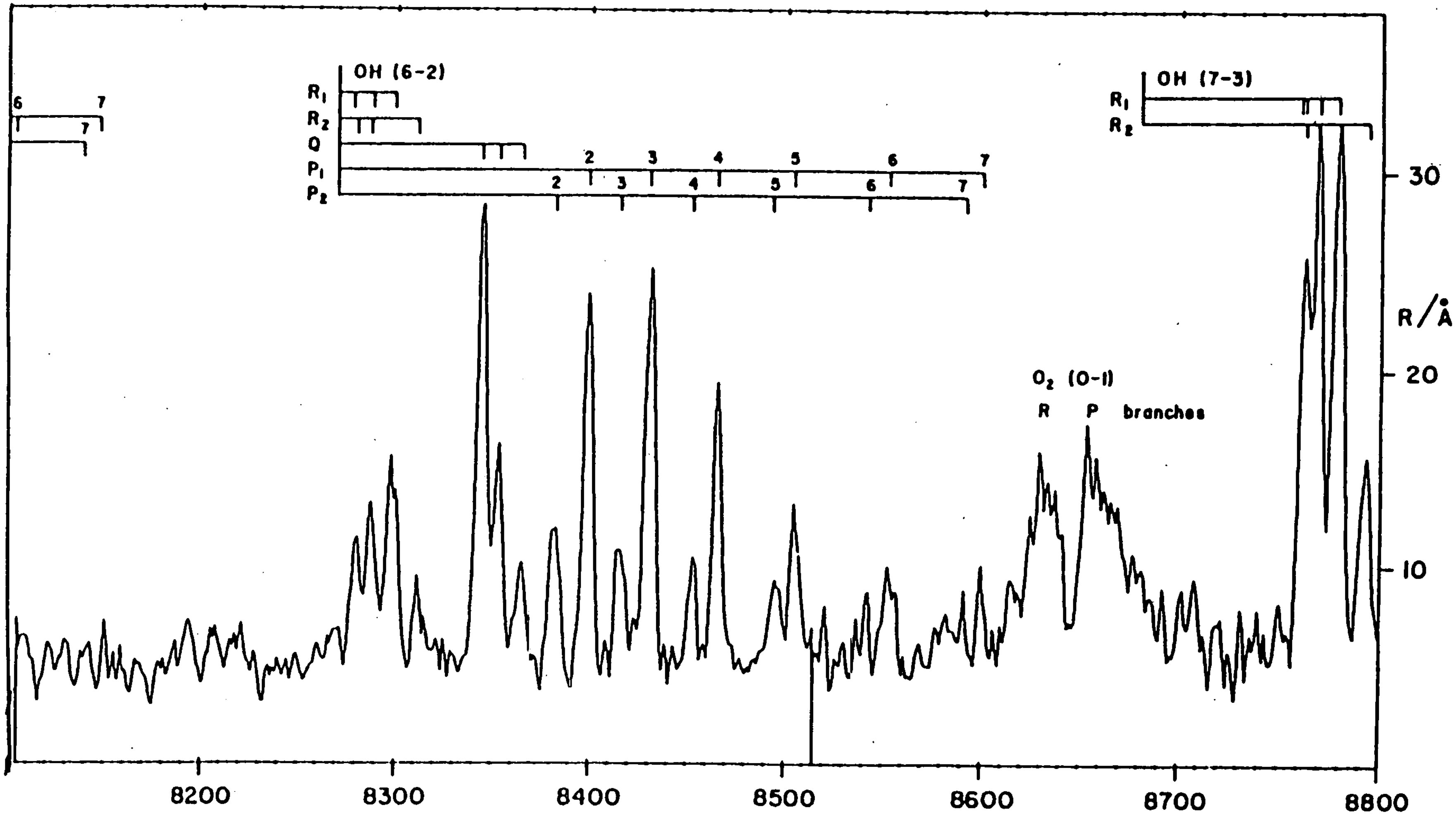
6
7
30
R/Å
20
10
O₂ (0-0)
A-band absorption
7400
7500
7600
7700
7800
7900
8000
Å
8100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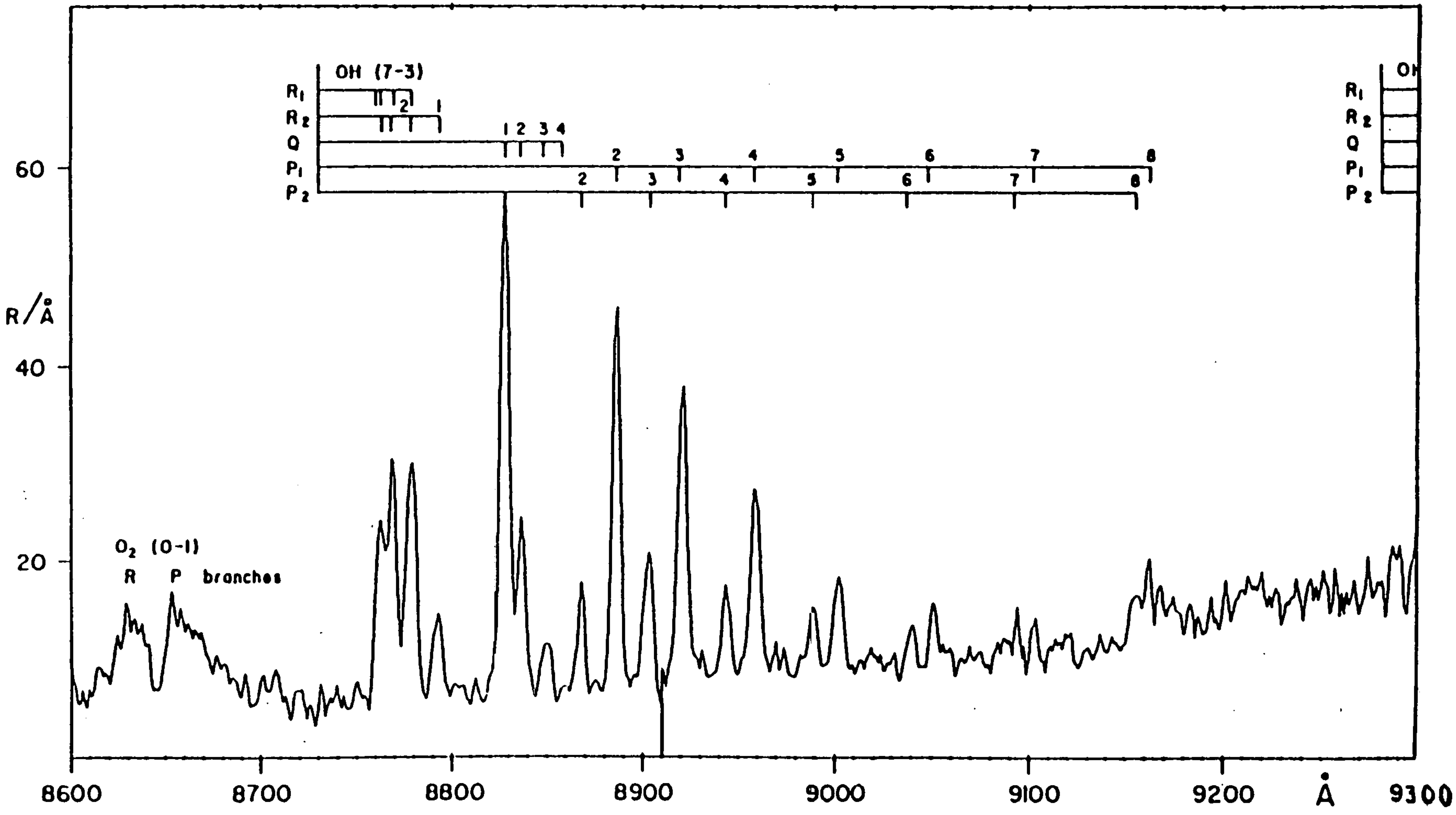
R₁
R₂
Q
P₁
P₂
6
7
7
2
3
4
5
6
7
2
3
4
5
6
7
OH (7-3)
R₁
R₂
O₂ (0-1)
R
P
branches
R/Å
30
20
10
8200
8300
8400
8500
8600
8700
8800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R₂
Q
P₁
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R₂
Q
P₁
P₂
60
R/Å
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R P branches
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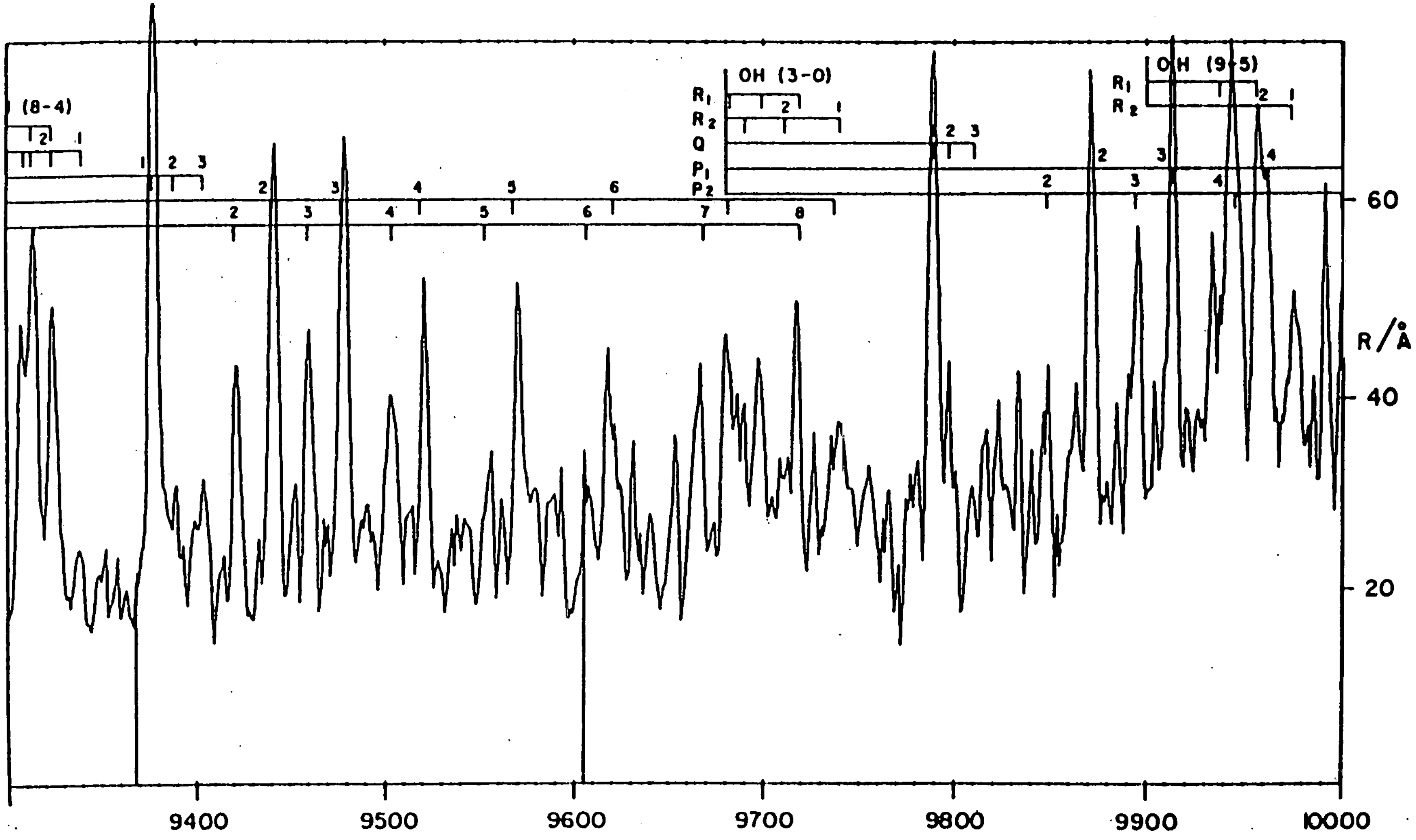
9100
9200
Å
9300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R₁
R₂
Q
P₁
P₂
OH (9-5)
R₁
R₂
1
2
3
4
5
6
7
8
R/Å
60
40
20
9400
9500
9600
9700
9800
9900
10000

ATLAS

OF THE AURORAL SPECTRUM

BY

A. VALLANCE JONES

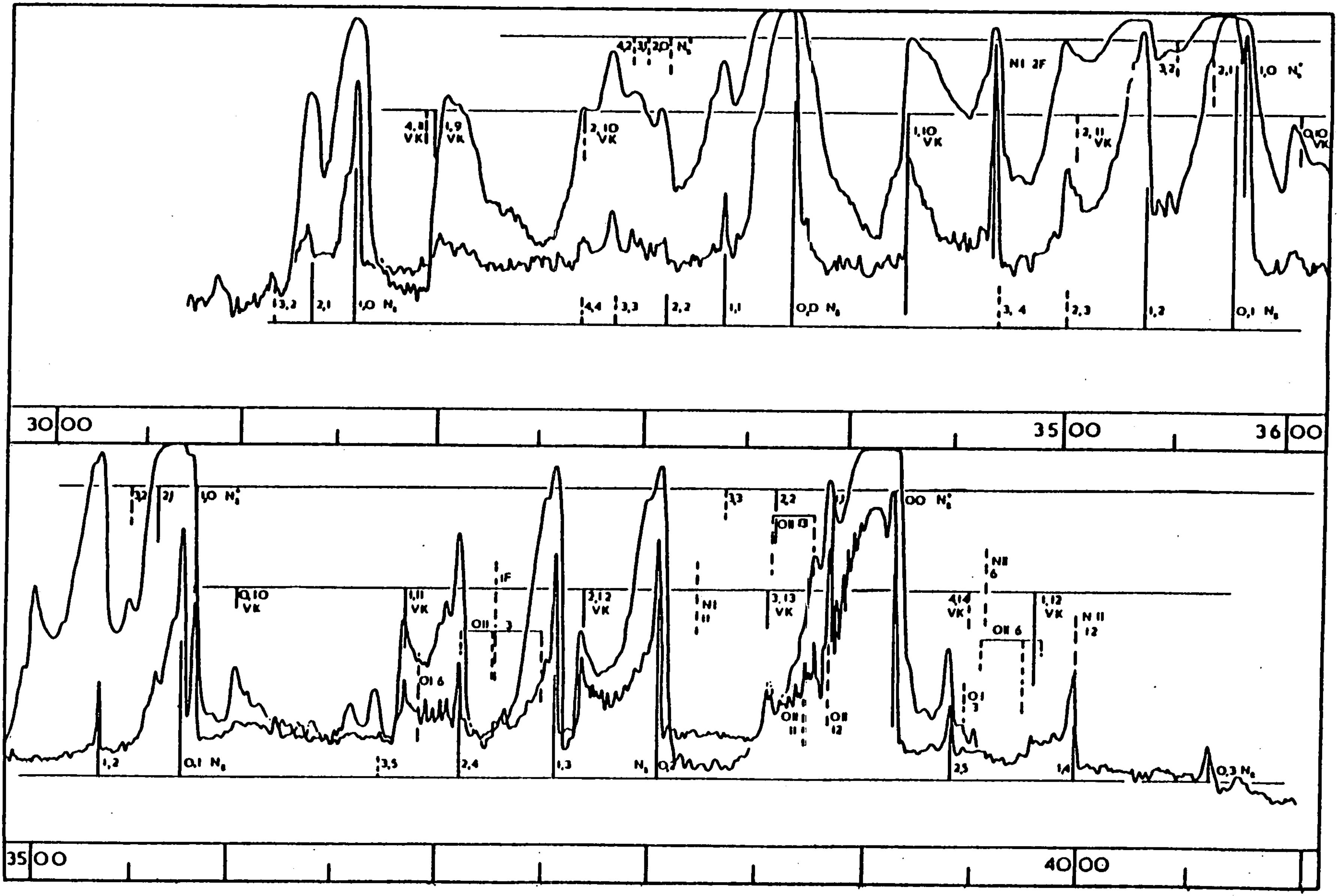
SCIENTIFIC REPORT

No. AR-20, 1955

PHYSICS DEPARTMENT

UNIVERISTY OF SASKATCHEWAN

Position of the bands and of the lines with their multiplet numering are from Chamberlain, J.W. and Oliver, N.J., J. Geophys. Res., 53, 457-472, 1953.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2,1
1,0 N2+
0,10 VK
3,2
2,1
1,0 N2
4,4
3,3
2,2
1,1
0,0 N2
3,4
2,3
1,2
0,1 N2
30|00
35|00
36|00
3,2
2,1
1,0 N2+
0,10 VK
1,11 VK
1F
O II 3
O I 6
2,12 VK
N I 11
3,3
2,2
O II 13
1,1
0,0 N2+
3,13 VK
O II 11
O II 12
4,14 VK
N II 6
O II 6
O I 3
1,12 VK
N II 12
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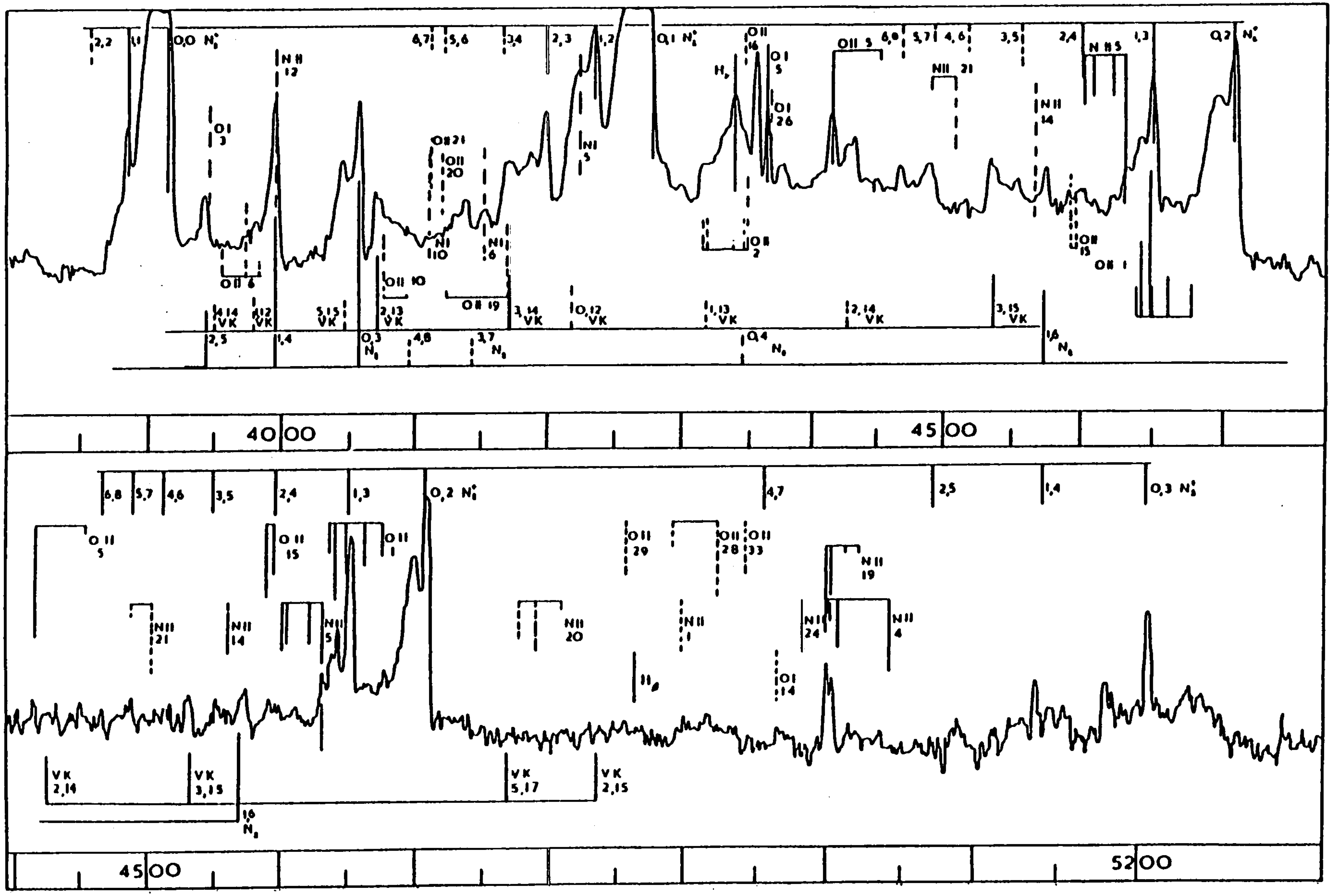
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1,4
0,3 N_2
2,13 VK
O II 10
4,8
O II 21
O II 20
N I 10
4,7
5,6
3,7 N_2
N I 6
O II 19
3,4
3,14 VK
2,3
N I 5
0,12 VK
1,2
0,1 N_2^+
H_γ
O II 16
O I 5
O I 26
O II 2
1,13 VK
0,4 N_2
O II 5
6,8
5,7
4,6
N II 21
2,14 VK
3,5
N II 14
3,15 VK
1,6 N_2
2,4
N II 5
O II 15
O II 1
1,3
0,2 N_2^+
40|00
45|00
6,8
5,7
4,6
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0,2 N_2^+
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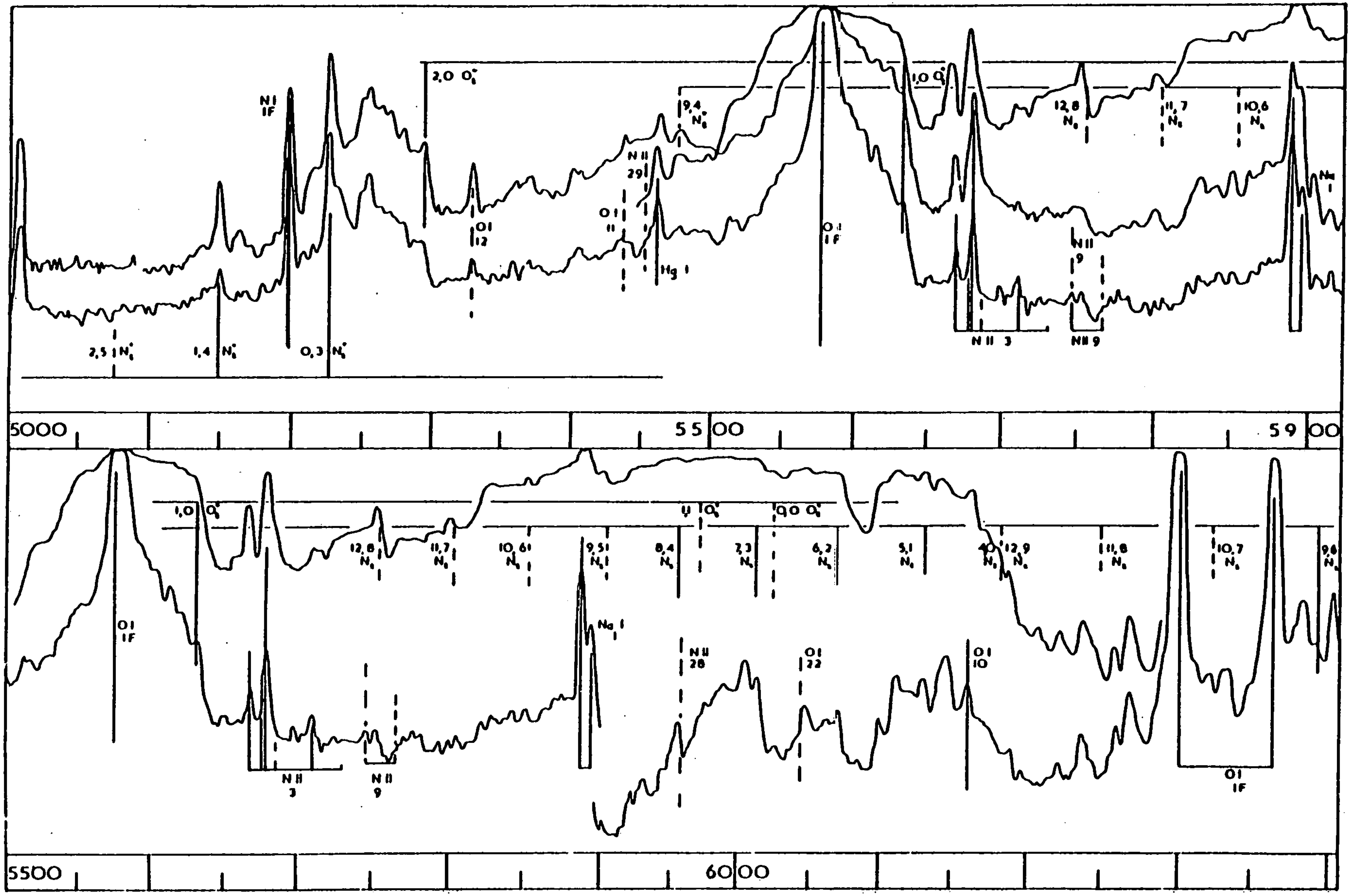
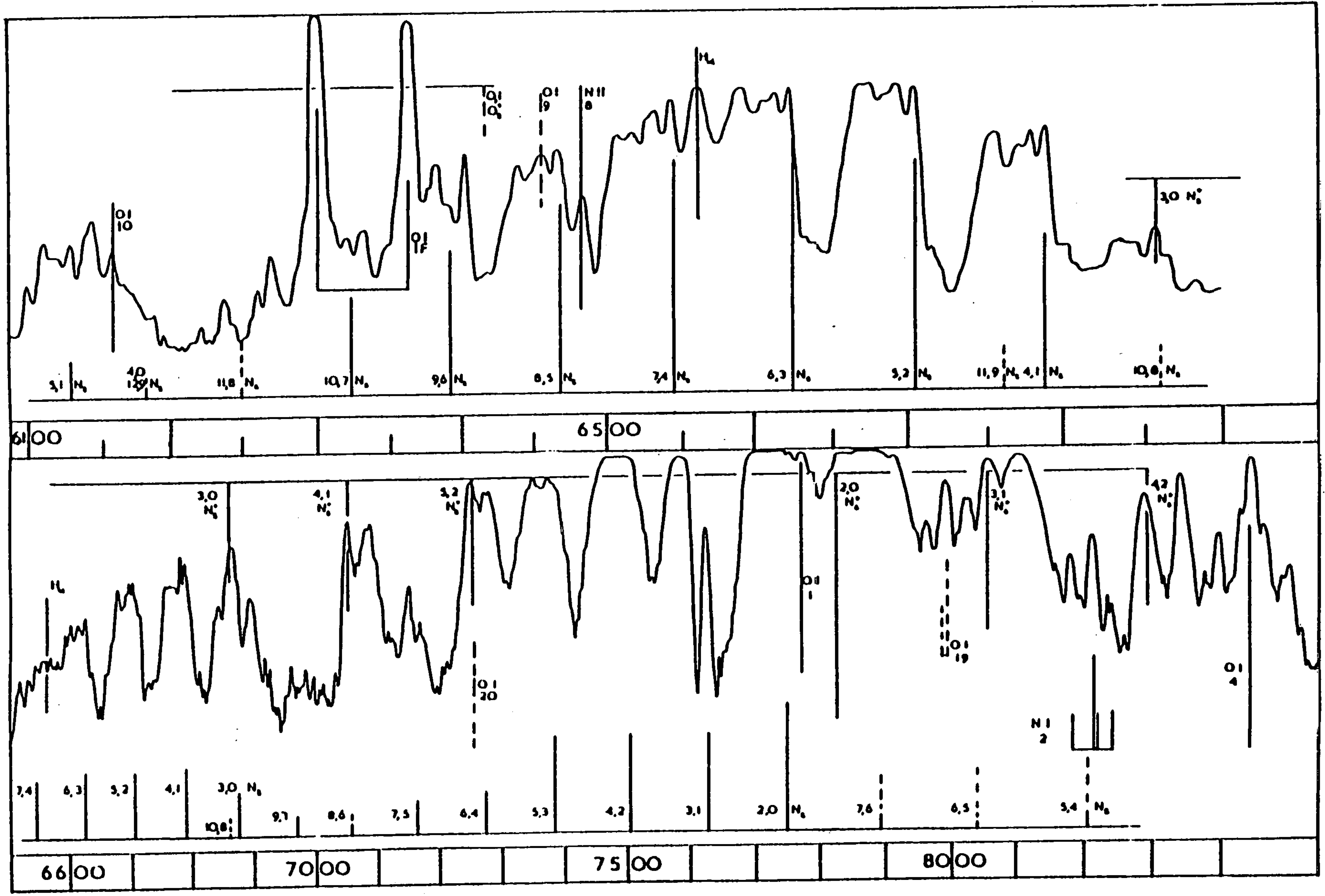
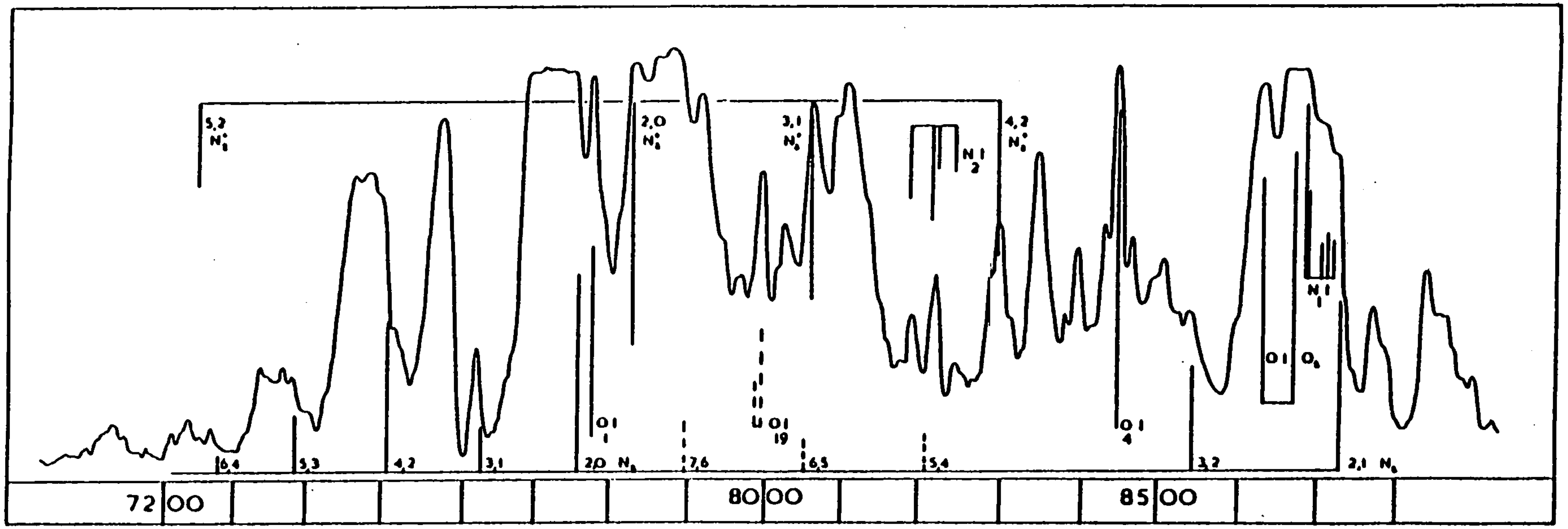
O II 15
O II 1
N II 21
N II 14
N II 5
VK 2,14
VK 3,15
1,6 N_2
N II 20
VK 5,17
VK 2,15
O II 29
H_β
N II 1
O II 28
O II 33
4,7
O I 14
N II 24
N II 19
N II 4
2,5
1,4
0,3 N_2^+
45|00
52|00


N I
1F
2,0 O₂⁺
9,4 N₂⁺
N II
29
O I
11
O I
12
Hg I
O I
1F
1,0 O₂⁺
12,8 N₂
11,7 N₂
10,6 N₂
Na
I
N II
9
N II 3
N II 9
2,5 N₂⁺
1,4 N₂⁺
0,3 N₂⁺
5000
55|00
59|00
1,0 O₂⁺
O I
1F
12,8 N₂
11,7 N₂
10,6 N₂
9,5 N₂
8,4 N₂
1,1 O₂⁺
7,3 N₂
0,0 O₂⁺
6,2 N₂
5,1 N₂
4,0 N₂
12,9 N₂
11,8 N₂
10,7 N₂
9,6 N₂
Na I
I
N II
28
O I
22
O I
10
N II
3
N II
9
O I
1F
5500
60|00


O I 10
O I O_2^+
O I 9
N II 8
H_α
O I F
3,0 N_2^+
5,1 N_2
4,0 12,9 N_2
11,8 N_2
10,7 N_2
9,6 N_2
8,5 N_2
7,4 N_2
6,3 N_2
5,2 N_2
11,9 N_2
4,1 N_2
10,8 N_2
61|00
65|00
3,0 N_2^+
4,1 N_2^+
5,2 N_2^+
H_α
O I 20
O I 1
2,0 N_2^+
O I 19
3,1 N_2^+
4,2 N_2^+
N I 2
O I 4
7,4
6,3
5,2
4,1
3,0 N_2
10,8
9,7
8,6
7,5
6,4
5,3
4,2
3,1
2,0 N_2
7,6
6,5
5,4 N_2
66|00
70|00
75|00
80|00


5,2 N₂⁺
2,0 N₂⁺
3,1 N₂⁺
4,2 N₂⁺
N I 2
N I 1
O I 1
O I 19
O I 4
O I
O₂
6,4
5,3
4,2
3,1
2,0 N₂
7,6
6,5
5,4
3,2
2,1 N₂
72|00
80|00
85|00