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Rocket and Satellite Investigations of the Ionosphere

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General. In the triennium, a wealth of information was gathered on the temporal, spatial, and energy distribution of low-energy particles in all subdivisions of the ionosphere including the previously relatively unexplored regions above the F_2 peak.

The D region under quiet solar conditions. *Nicolet and Aikin* [1960] proposed that the *D* region (50 to 85 km) is ionized by cosmic radiation below 70 km and in the 70- to 85-km region by Lyman-α radiation acting on a minor constituent, nitric oxide. On the other hand, *Poppoff and Whitten* [1962] suggest that the upper *D* region is characterized by a lower charged particle concentration resulting entirely from 2 to 8A X rays. *Smith* [1961] and *Aono et al.* [1961] using rocket-borne dc probes with different methods of analyses reported positive ion density values systematically higher than even the Nicolet-Aikin model. *Whipple* [1960], working with rocket measurements of ion conductivity [*Bourdeau et al.*, 1959], computed a negative ion density profile showing an abundance higher than all theoretical estimates including those of *Moler* [1960].

Important contributions to *D*-region physics have come from long-term satellite observations which show the Lyman-α flux to be relatively constant with solar activity whereas the flux of 2 to 8A X rays is extremely variable [*Kreplin et al.*, 1962]. Solar radiation data important to *D*-region ionization also are being obtained from the Orbiting Solar Observatory [*Lindsay*, 1962] and the Ariel satellite [*Pounds and Willmore*, 1962].

The disturbed D region. An empirical correlation has been found between sudden ionospheric disturbances and the times when the energy flux of 2 to 8A X rays measured on the Greb satellite exceeded a critical value of 2×10^{-3} erg cm^{-2} sec^{-1} [*Friedman*, 1962]. Rocket measurements of electron collision frequency and density were obtained during the early phases of a polar cap absorption [*Kane*, 1960]. A time history of *D*-region electron density profiles during an entire polar cap absorption event has been proposed by *Maehlum and O'Brien* [1962], by inserting proton fluxes measured on the Injun satellite into a conventional equation of ionization and correlating the results in time with riometer absorption observations.

Ion content of the lower ionosphere. Altitude-dependent models of the production rates of individual ionic species, principally N_2^+, O_2^+, and O^+, have been proposed by *Watanabe and Hinteregger* [1962] from rocket data obtained by the latter on solar ultraviolet intensities. These are considered qualitative because of the uncertainty in atmospheric composition. Some insight into the important ionospheric reactions can be made by comparing these results with rocket observations of the relative ion abundance. The rocket ion spectrometer results of *Johnson et al.* [1958] which were obtained at auroral latitudes now have been extended to midlatitudes by *Taylor and Brinton* [1961]. The latter results confirm the predominance of the diatomic ions (NO^+, O_2^+) below 200 km and of O^+ above this altitude but place a greater emphasis on NO^+.

Electron densities in the lower ionosphere. *Hinteregger and Watanabe* [1962], again using Hinteregger's rocket observations of solar radiation intensity, suggested the relative importance of individual wavelength bands to the formation of the classical ionospheric regions, their most controversial conclusion being a contradiction that *E*-region ionization is due to soft X rays. New rocket methods of electron density determination were developed, principally an RF probe operating above the plasma frequency [*Jackson and Kane*, 1960] and an asymmetric Langmuir probe [*Smith* 1961]. With the latter device, *Smith* [1962] has studied the nighttime *E* region, finding a two-order magnitude decrease from average daytime electron densities. Values of 3 and 1×10^3 electrons cm^{-3} were measured in the 100- to 115-km region at 22 h and near sunrise, respectively. These nighttime profiles show a pronounced valley above 115 km.

Smith [1962] experimentally defined one type of sporadic E in terms of an ionization enhancement of about a factor of 4 confined to a depth of less than 0.5 km with a horizontal dimension greater than 72 km. He suggests that these characteristics are similar to those which led *Whitehead* [1960] to propose that some types of E_s are caused by redistribution of electrons by wind shear rather than local changes in electron production or loss.

The availability of electron density profiles obtained from rockets flown above the F_2 peak resulted in new attempts at empirical models which interrelate the shape, the maximum electron density, and the 'scale height' of the F_2 peak. These empirical models vary in complexity from the use of a constant scale height [*Wright,* 1960], a scale height gradient [*Yonezawa and Takahashi,* 1959], and a variable scale height gradient [*Chandra,* 1963]. The controversy over the relative influences of diffusion and radiative recombination near the F_2 peak continues [cf. *Sagalyn et al.*, 1963].

The upper ionosphere. Satellite measurements of charged particle density were made by the use of ion traps [*Bourdeau;* 1961] and RF probes [*Bourdeau and Bauer,* 1962; *Sayers et al.,* 1962]. Sayers et al., working with profiles constructed from Ariel satellite data, claim to have discovered ionization ledges at all latitudes between 0° and 55° varying from 1200 km at local midnight down to 600 km at midday. On the other hand, charged particle density profiles with practically constant electron-ion scale heights between 400 and 700 km were obtained at midlatitudes from rockets by radio-propagation methods [*Berning,* 1960; *Jackson and Bauer,* 1961; *Bauer and Jackson,* 1962; *Knecht and Russell,* 1962], by the use of ion traps [*Hanson and McKibbin,* 1961; *Hale,* 1961], and by RF probes [*Ulwick and Pfister,* 1962]. Their preferred conclusion is that the upper ionosphere is isothermal and in diffusive equilibrium with changes in electron-ion scale height due to corresponding changes in the ionic mixture. *Knecht et al.* [1961] obtained important diagnostic information on field-aligned irregularities from a rocket test of the topside sounding technique in a spread-F condition.

Hanson [1962*a*], working with Hale's ion density profile, concluded that a 2000-km-thick helium ion layer lies between the upper F region (where O^+ is dominant) and the protonosphere. The first direct evidence for the importance of helium ions was obtained by the use of an ion trap flown on Explorer 8 [*Bourdeau et al.,* 1962]. *Mange* [1960] set forth the governing equations for the electron density distribution in a multi-constituent ionosphere in diffusive equilibrium. *Bauer* [1962, 1963] proposed that the thickness of the helium ion layer should be strongly dependent on the atmospheric temperature. This has been corroborated by *Willmore et al.* [1962] who, by the use of an ion trap on the Ariel satellite, report He^+ predominant from 950 km to apogee (1200 km) for a daytime condition, but with protons becoming important near apogee at night. The large variability of upper ionosphere ion transition altitudes is also confirmed by the preliminary results from the Alouette topside sounder satellite [*Nelms,* 1963; *King,* 1963; *Knecht and Van Zandt,* 1963]. *Bourdeau* [1963] points out that the end result is a higher electron density above 1000 km at night than during the day.

Electron temperatures. Theoretical calculations of electron temperatures based on the assumption of solar radiation as the only ionizing source were made by *Hanson and Johnson* [1961] and more recently by *Hanson* [1962*b*] and *Dalgarno et al.* [1962]. Observational data have been reviewed by *Bauer and Bourdeau* [1962]. *Serbu et al.* [1961], using a gridded Langmuir probe on Explorer 8, obtained values of 1000° ± 200°K and 1800° ± 200°K as the extremes of the diurnal electron temperature variation above 450 km during November 1960. *Aono et al.* [1961], using a rocket-borne resonance probe, obtained electron temperature values which caused them to conclude temperature equilibrium at E-region altitudes. *Spencer et al.* [1962] obtained electron temperature data from a symmetric Langmuir probe at altitudes between 100 km and the F_2 peak. They concluded for an auroral and/or a disturbed ionosphere that significant departures from temperature equilibrium could be expected at all altitudes of their flights. The data from one of the flights were obtained at midlatitudes in a quiet ionosphere and show lower electron temperatures in the E and F_2 regions than the other three flights. *Willmore et al.* [1962] have measured the diurnal electron temperature variation in the isothermal region above 400 km for May 1962, and propose a latitude dependence with midday values of 1200°K at the equator and 1600°K at 55°, all having a pronounced high value during the sunrise period.

Electron content. Radio transmissions from satellites have been used extensively for determination of electron content between observing sites and altitudes well above the F_2 peak. *Yeh and Swenson* [1961] reveal strong diurnal and anomalous seasonal variation as well as a depression of electron content during magnetic storms. *Garriott* [1960] reports gross effects of large magnetic storms on the electron content and the ratio of the electron content above the F_2 peak to the content below. *Ross* [1960] emphasizes strong seasonal effects and magnetic control of the summer ionosphere. *Blumle* [1962] obtains a diurnal variation at the magnetic equator which is empirically in phase with the diurnal variation of atmospheric temperature.

Satellite reception of very low frequency. Reception of VLF signals on spacecraft was obtained for the first time. *Cain et al.* [1961] detected lightning induced whistlers on the Vanguard 3 satellite and emphasized low nighttime absorption by the ionosphere and a high occurrence near the equator. *Leiphart et al.* [1962] reported reception of VLF on the Lofti satellite from transmitters on the Earth's surface and also noted less attenuation at night with reception as far away as 10,000 miles. They observed little attenuation with altitude and 18-kc time delays from 10 to 200 msec. *Rorden et al.* [1962] reported Lofti reception of 18-kc signals virtually everywhere by the whistler mode in the ionosphere, with signal attenuation dependent on the direction of the transmitter. They observed one-hop echo delays of 20 to 50 msec, and strong two-hop whistler echoes sometimes exceeding the direct signal at the satellite.

References

Aono, Y.. K. Hirao, and S. Miyazaki, Positive ion density, electron density and electron temperature in the ionosphere, *J. Radiation Res. Lab., Japan, 8,* 453–465, 1961.

Bauer, S. J., On the structure of the topside ionosphere, *J. Atmospheric Sci., 19,* 276–278, 1962.

Bauer, S. J., Helium ion belt in the upper atmosphere, *Nature, 197,* 1963.

Bauer, S. J., and R. E. Bourdeau, Upper atmosphere temperatures derived from charged particle observations, *J. Atmospheric Sci., 19,* 218–225, 1962.

Bauer, S. J., and J. E. Jackson, Rocket measurement of the electron density distribution in the topside ionosphere, *J. Geophys. Res., 67,* 1675–1677, 1962.

Berning, W. W., A sounding rocket measurement of electron densities to 1500 kilometers, *J. Geophys. Res., 65,* 2589–2594, 1960.

Blumle, L. J., Satellite observations of the equatorial ionosphere, *J. Geophys. Res., 67,* 4601–4605, 1962.

Bourdeau, R. E., Ionospheric results with sounding rockets and satellites, *Space Research II,* edited by H. C. van de Hulst, C. de Jager, and A. F. Moore, pp. 554–573, North-Holland, Amsterdam, 1961.

Bourdeau, R. E., Ionospheric research from space vehicles, *Space Sci. Rev.,* in press, 1963.

Bourdeau, R. E., and S. J. Bauer, Structure of the upper atmosphere deduced from charged particle measurements on rockets and the Explorer 8 satellite, *Space Research III,* edited by W. Priester, North-Holland, Amsterdam, to be published, 1962.

Bourdeau, R. E., J. L. Donley, E. C. Whipple, and S. J. Bauer, Experimental evidence for the presence of helium ions based on Explorer 8 satellite data, *J. Geophys. Res., 67,* 467–475, 1962.

Bourdeau, R. E., E. C. Whipple, and J. F. Clark, Analytic and experimental electrical conductivity between the stratosphere and the ionosphere, *J. Geophys. Res., 64,* 1363–1370, 1959.

Cain, J. C., I. R. Shapiro, J. D. Stolarik, and J. P. Heppner, A note on whistlers observed above the ionosphere, *J. Geophys. Res., 66,* 2677–2680, 1961.

Chandra, S., Electron density distribution in the upper *F* region and related atmosphere parameters, *J. Geophys. Res., 68,* 1937–1942, 1963.

Dalgarno, A., M. B. McElroy, and R. J. Moffett, Electron temperatures in the ionospheres, *Geophys. Corp. Am. Tech. Rept. 62-11-N,* 1962.

Friedman, H., Solar radiation, *Astronautics, 8,* 14–23, 1962.

Garriott, O. K., The determination of ionospheric electron content and distribution from satellite observations, *J. Geophys. Res., 65,* 1139, 1960.

Hale, L. C., Ionospheric measurements with a multigrid retarding potential analyzer, *J. Geophys. Res., 66,* 1954, 1961.

Hanson, W. B., Upper atmosphere helium ions, *J. Geophys. Res., 67,* 183–188, 1962*a*.

Hanson, W. B., Electron temperatures in the upper atmosphere, *Space Research III,* edited by W. Priester, North-Holland, Amsterdam, to be published, 1962*b*.

Hanson, W. B., and F. S. Johnson, Electron temperatures in the ionosphere, *Les Congrès et Colloques de l'Université de Liège, 20,* 390–424, 1961.

Hanson, W. B., and D. D. McKibbin, An ion-trap measurement of the ion concentration profile

above the F_2 peak, *J. Geophys. Res., 66,* 1667–1671, 1961.
Hinteregger, H. E., and K. Watanabe, Photoionization rates in the *E* and *F* regions, 2, *J. Geophys. Res., 67,* 3373–3392, 1962.
Jackson, J. E., and S. J. Bauer, Rocket measurement of a daytime electron density profile up to 620 km, *J. Geophys. Res., 66,* 3055–3057, 1961.
Jackson, J. E., and J. A. Kane, Ionospheric measurements using environmental sampling techniques, *Space Research I,* edited by H. Kallmann-Bijl, pp. 328–339, North-Holland, Amsterdam, 1960.
Johnson, C. Y., E. B. Meadows, and J. C. Holmes. Ion composition of the arctic ionosphere, *J. Geophys. Res., 63,* 443–444, 1958.
Kane, J. A., Reevaluation of ionospheric electron densities and collision frequencies derived from rocket measurements of refractive index and attenuation, *NASA Tech. Note D-503,* 1960.
King, J. W., Preliminary studies of the upper ionosphere deduced from topside sounder data, *Nature,* in press, 1963.
Knecht, R. W., and S. Russell, Pulsed radio soundings of the topside of the ionosphere in the presence of spread *F, J. Geophys. Res., 67,* 1178–1182, 1962.
Knecht, R. W., and T. E. Van Zandt, Some early results from the ionospheric topside sounder satellite, *Nature,* in press, 1963.
Knecht, R. W., T. E. Van Zandt, and S. Russell, First pulsed radio soundings of the topside of the ionosphere, *J. Geophys. Res., 66,* 3078–3082, 1961.
Kreplin, R. W., T. A. Chubb, and H. Friedman, X-ray and Lyman-alpha emission from the Sun as measured from the NRL SR-1 satellite, *J. Geophys. Res., 67,* 2231–2253, 1962.
Leiphart, J. P., R. W. Zeek, L. S. Bearce, and E. Tóth, Penetration of the ionosphere by very-low-frequency radio signals, *Proc. IRE, 50,* 16–17, 1962.
Lindsay, J. C., Solar radiation in the ultraviolet and X-ray spectrum, *Intern. Symp. on Space Phenomena* (IRE/NASA/AEC), 1962.
Maehlum, B., and B. J. O'Brien, Solar cosmic rays of July 1961, and their ionospheric effects, *J. Geophys. Res., 67,* 3281–3288, 1962.
Mange, P., The distribution of minor ions in electrostatic equilibrium in the high atmosphere, *J. Geophys. Res., 65,* 3833–3834, 1960.
Moler, W. F., VLF propagation effects of a *D*-region layer produced by cosmic rays, *J. Geophys. Res., 65,* 1459–1468, 1960.
Nelms, G. L., Scale heights of the upper ionosphere from topside soundings, *Nature,* in press, 1963.
Nicolet, M., and A. C. Aikin, The formation of the *D*-region of the ionosphere, *J. Geophys. Res., 65,* 1469–1483, 1960.
Poppoff, I. G., and R. C. Whitten, *D*-region ionization by solar X rays, *J. Geophys. Res., 67,* 2986–2989, 1962.
Pounds, K., and A. P. Willmore, X-ray measurements on the Ariel satellite, *Proc. Intern. Conf. on the Ionosphere,* in press, 1962.
Rorden, R., R. L. Smith, and R. A. Helliwell, An interpretation of Lofti VLF observations, *AGARD, Munich.* September 1962.
Ross, W. J., The determination of ionospheric electron content from satellite Doppler measurements, *J. Geophys. Res., 65,* 2601, 1960.
Sagalyn, R. C., M. Smiddy, and J. Wisnia, Measurement and interpretation of ion density distributions in the daytime *F* region, *J. Geophys. Res., 68,* 199–211, 1963.
Sayers, J., P. Rothwell, and J. H. Wager, Evidence for a further ionospheric ledge above the F_2 region, *Nature, 195,* 1143–1145, 1962.
Serbu, G. P., R. E. Bourdeau, and J. L. Donley, Electron temperature measurements on the Explorer 8 satellite, *J. Geophys. Res., 66,* 4313–4319, 1961.
Smith, L. G., Electron density measurements by the asymmetric probe, *J. Geophys. Res., 66,* 2562, 1961.
Smith, L. G., Rocket measurements of electron density and temperature in the nighttime ionosphere, *J. Geophys. Res., 67,* 1658, 1962.
Spencer, N. W., L. H. Brace, and G. R. Carignan, Electron temperature evidence for nonthermal equilibrium in the ionosphere, *J. Geophys. Res., 67,* 157–175, 1962.
Taylor, H. A., and H. C. Brinton, Atmospheric ion composition measured above Wallops Island, Virginia, *J. Geophys. Res., 66,* 2587–2588, 1961.
Ulwick, J. C., and W. Pfister, Spatial and temporal variations of electron density from an orbiting satellite, *Space Research III,* edited by W. Priester, North-Holland, Amsterdam, to be published, 1962.
Watanabe, K., and H. E. Hinteregger, Photoionization rates in the *E* and *F* regions, 1, *J. Geophys. Res., 67,* 999–1006, 1962.
Whipple, E. C., Direct measurements of ion density and conductivity in the *D*-region, *XIth Intern. Astron. Congress,* 99–102, 1960.
Whitehead, J. D., Formation of the sporadic-*E* layer in temperate zones, *Nature, 188,* 567, 1960.
Willmore. A. P., R. L. F. Boyd, and P. J. Bowen, Some preliminary results of the plasma probe experiments on the Ariel satellite, *Proc. Intern. Conf. on the Ionosphere,* in press, 1962.
Wright, J. W., A model of the *F*-region above $h_{max}F_2$, *J. Geophys. Res., 65,* 195, 1960.
Yeh, K. C., and G. W. Swenson, Ionospheric electron content and its variation deduced from satellite observations, *J. Geophys. Res., 66,* 1061–1068, 1961.
Yonezawa, T., H. Takahashi, and Y. Arima, A theoretical consideration of the electron and ion density distributions in the lower portion of the *F*-region, *J. Radiation Res. Lab., Japan, 6,* 21–40, 1959.