

The aurora borealis has long been a fascinating subject and many studies have been made to help man appreciate this most unusual phenomenon. One of the most rewarding methods of studying the aurora has been by the use of rockets. This article discusses a series of experimental rocket firings, some of the techniques used in auroral research, and some of the resultant data.

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ROCKETS and the AURORA BOREALIS

Here in Maryland the displays of “northern lights” are very weak and infrequent—so much so that most Marylanders are not even aware of their occurrence. It is, however, a spectacular and nightly occurrence for those few people who live in two narrow bands extending only a few degrees in latitude and centered on 68° north and south magnetic latitude. In these regions the displays can be bright enough to rival the full moon in lighting up the landscape; can show every color of the spectrum; and can present a bewildering variety of shapes and forms (Fig. 1), which are sometimes stationary and sometimes flash across the sky at speeds comparable to the fastest reported UFO.

A particularly vivid description of an aurora was given many years ago by Hayes¹:

The darkness was so profound as to be oppressive. Suddenly, from the rear of the black cloud which obscured the horizon, flashed a bright ray. Presently an arch of many colours fixed itself across the sky, and the aurora gradually developed.

The space within the arch was filled by the black cloud; but its borders brightened steadily, though the rays discharged from it were exceeding capricious, now glaring like a vast conflagration, now beaming like the glow of a summer morn. More and more intense grew the light, until, from irregular bursts, it matured into an almost uniform sheet of radiance. Towards the end of the display its character changed. Lurid fires flung

their awful portents across the sky, before which the stars seemed to recede and grow pale.

The colour of the light was chiefly red; but every tint had its turn, and sometimes two or three were mingled; blue and yellow streamers shot across the terrible glare, or, starting side by side from the wide expanse of the radiant arch, melted into each other, and flung a strange shade



Fig. 1—An aurora at Fort Churchill. Most displays are greenish-blue, but highly active aurorae contain all colors. (Stars appear as white specks in photograph.)

¹ J. R. Capron, “Aurorae: Their Characters and Spectra,” Spon, Ltd., London, 1879.

of emerald over the illuminated landscape. Again this green subdues and overcomes the red; then azure and orange blend in rapid flight, subtle rays of violet pierce through a broad flash of yellow, and the combined streams issue in innumerable tongues of white flame, which mount towards the zenith.

If these displays had existed at more temperate latitudes during our early civilization, an entirely different mythology would have developed.

It is only natural that such magnificent phenomena would be the subject of much study, not only today but for many years past. However, despite the tremendous amount of research performed in this area, there are still many questions requiring study. Not only are many of the smaller details not understood, but even the most basic question—"What is the auroral mechanism?"—is still unanswered.

Auroral Research

Auroral research covers many fields of physics, and can be categorized from several different viewpoints. The first is to consider the aurora as the end product of a large-scale cosmic phenomenon which has taken place between the sun and the earth. It looks upon the earth's atmosphere as a gigantic scintillation counter that can yield information regarding the energy, distribution, and nature of the bombarding particles that are believed to be the immediate cause of the emitted radiation. Using this information, it attempts to work backward through the successive chain of events and to eventually explain the larger cosmic phenomenon.

A second is to consider the upper atmosphere as a voluminous laboratory in which the aurora is used as the basis for such studies as plasma physics, magnetohydrodynamics, and atomic and molecular processes. Many processes have been found to occur in this region that are extremely difficult, if not impossible, to study in our own laboratories, such as certain atomic and molecular deactivation and charge transfer mechanisms.

A third viewpoint is to consider only the upper atmosphere itself and the effect that the aurora has upon it. Thus, how the bombarding particles reach the ionosphere is of no consequence since the concern here is only for what happens to them once they do arrive. The aurora is, therefore, used as a tool for determining such information about the atmosphere as its composition and temperature as a function of altitude.

Ground-based measurements have been seriously limited by the opacity of the lower atmosphere and the lack of detailed height resolution. They have consisted primarily of morphological and spec-



Fig. 2—Entrance to the rocket range at Fort Churchill.

trometric studies of the visible light emissions, coupled with other information obtained from magnetometers and radiosondes. It was the advent of the sounding rocket, however, that gave great impetus to research in this area. Then, for the first time, it was possible to measure the altitude variation of the various spectral emissions with high-speed scanning spectrometers and photometers; to identify and measure the spatial and energy distributions of the charged particles which produce the aurora and do not penetrate to ground level; and to observe radiation over the entire electromagnetic spectrum, only a small fraction of which, mainly in the visible region, can be observed from the ground or even from the highest balloon.

Even today scientific studies of auroral phenomena are seriously limited because of the remote location of the zone. Although, at present, Fort Churchill, Manitoba, Canada, (Figs. 2 and 3) is the only site in the auroral zone from which sounding rockets can be launched, in the past decade many rockets have been launched from that site.

Visual and spectroscopic studies of aurorae were carried out long before the space age. Crude altitude profiles, temperature determinations, and atmospheric composition are among the important results of these ground-based studies. One of the most spectacular results was the discovery, in the early 1950's, that occasionally aurorae are caused by protons which come directly from the sun as evidenced by the doppler shift of the $H\alpha$ radiation emitted *after* the protons had captured an electron in the earth's atmosphere. The ground-based studies play an important role in rocket research, not only by providing additional information during a rocket flight, but more importantly by providing guidelines to the type of research that needs to be done.



Fig. 3—Main street on a pleasant February evening.

The rocket is a particularly valuable tool for studying the interaction of the exciting particles with atmospheric species. The particles spiral down the magnetic field lines, which are near vertical in the auroral zone; thus, a vertically moving sounding rocket can study the interaction in the altitude range 100 to 200 km with the atmospheric pressure as an important and well known variable. However, the aurora particles may have first interacted with the earth's field at a hundred thousand kilometers, so that information about the particles and fields above the visible aurora are very important. This type of information can be obtained by satellites which can also observe the gross features of optical aurora below. A coordinated program of satellite and sounding rocket research will probably be required for completion of the auroral studies.

A good example of the many auroral problems that still confront us is the very basic problem of the determination of the origin of the exciting particles, and the physical mechanism which delivers them to the auroral zones. When the outer Van Allen belt was discovered, with its nearest approach to earth being directly above the auroral zone, it was thought that magnetic disturbances, which are closely correlated to auroral displays, could dump electrons from the belt, but recent quantitative considerations have shown that there are not enough particles stored in this belt to account for the observed auroral energy. No other storage bin has been discovered. The present theory suggests that the particles (which have been clearly established by rocket measurements to be predominantly electrons) originate in the solar wind with an energy of about 30 eV and are accelerated in the earth's magnetic field. Perturbations in the solar wind presumably distort the earth's magneto-

sphere to admit these electrons which are normally deflected around the earth. This theory is even more sketchy when it comes to the acceleration mechanism. Another model suggested by Dessler and Hanson² hypothesizes that there is actually no injection of solar plasma into the geomagnetic field at all—rather the terrestrial ions in the magnetosphere are energized by energy transfer at the interface.

The intensity of aurorae are described by a logarithmic intensity scale by Roman numerals I to IV. An Intensity IV aurora, which may occur only once a decade, gives a surface illumination equivalent to that of the full moon. Intensity I aurorae, one thousandth as bright, having about the brightness of the Milky Way, occur nightly and are easily visible to the dark-adapted eye. Intensities II and III aurorae (10 to 100 times as bright as those of Intensity I) are in the range of brightness desirable for spectroscopic studies.

Auroral Studies at The Johns Hopkins University

For the past six years a group in the Physics Laboratory at Homewood has been interested in auroral studies and has instrumented four Aerobee rockets, all of which were fired into active auroral discharges, and all of which provided information about the auroral process. The Applied Physics Laboratory has participated in this program from the beginning, having conducted the flight acceptance environmental tests for the earliest flight, and presently is providing the data processing necessary to analyze the results of the more sophisticated recent experiments.

The first rocket spectrometer which was used in this work is shown in Fig. 4. The large bottom section is an f/10 Ebert-type scanning spectrometer having a focal length of 50 cm. A typical grating would have 3600 lines/mm, a width of 64 mm, and an Al-MgF₂ coating to provide maximum reflection in the far ultraviolet (a region of principal interest). The cylindrical housing fastened to the top of the spectrometer contains all of the electronics and the four photomultiplier tubes required for the spectrometer, two photometers, and an electron sensor. The four forward extensions are light baffles. The first experiment with such an instrument took place in February 1960 and was primarily designed as an engineering test flight of the spectrometric equipment and a survey of the short-wavelength region for guidance in planning

² A. J. Dessler and W. B. Hanson, "Possible Energy Source for the Aurora," *Astrophys. J.*, **134**, 1963, 1024.

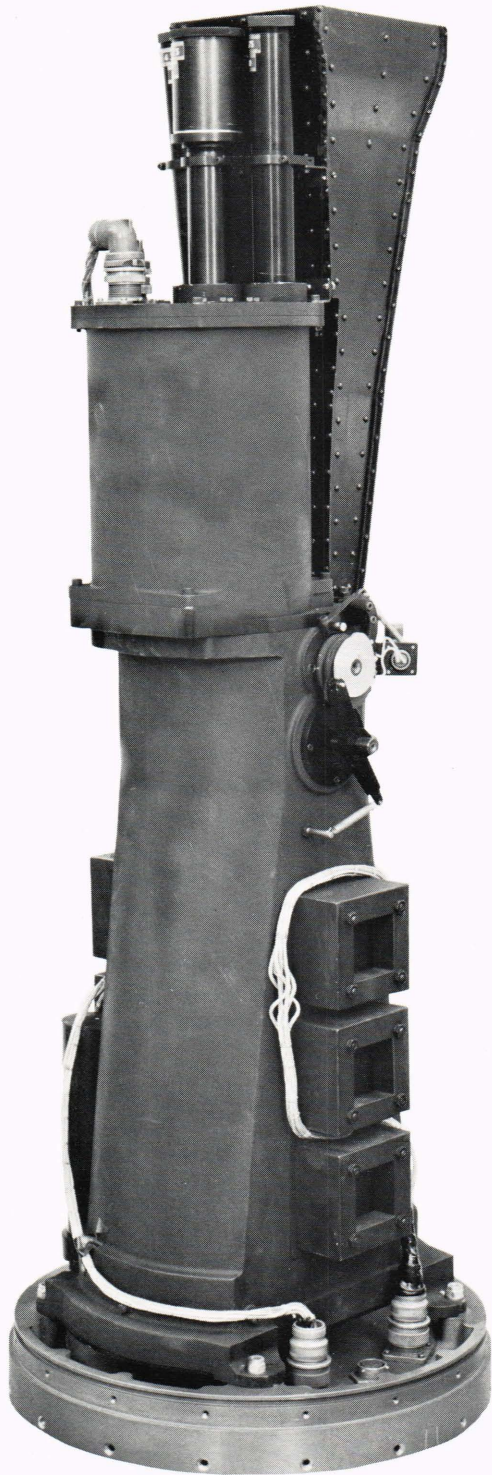


Fig. 4—The rocket spectrophotometer used for the JHU studies. A motor-driven cam drives a plane diffraction grating to scan the spectrum. The light signals at the exit slit are detected by a photomultiplier tube and the measured currents are telemetered to ground.

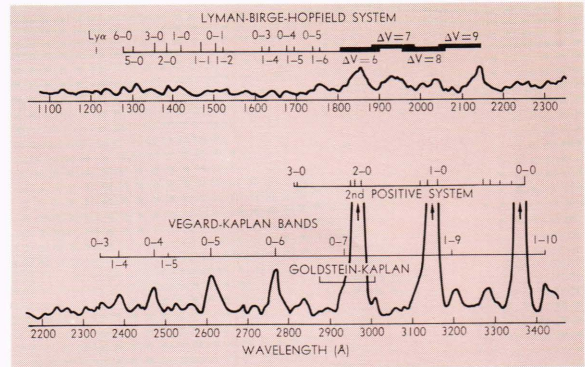


Fig. 5—The first far ultraviolet rocket spectrum (obtained in 1960). The spectroscopic nomenclature and locations of the various bands are indicated in the illustration.

future rocket experiments.³ This rocket obtained the first far ultraviolet spectrum of the aurora in an Intensity III display. A composite spectrum obtained from this flight is shown in Fig. 5 and the results can be summarized as follows:

1. Identification of the Lyman-Birge-Hopfield (L-B-H) bands between 1200 and 2200 Å.
2. Identification of the Goldstein-Kaplan (G-K) bands at 2863 and 3005 Å.
3. Identification and comparison of intensities of Vegard-Kaplan and Second Positive bands in the region 2200 to 3500 Å.
4. The detection of the Lyman α line of atomic hydrogen at 1216 Å, and possibly the atomic nitrogen line at 1134 Å.

The presence of the Vegard-Kaplan bands of molecular nitrogen in the aurora is a good example of processes that take place high in the atmosphere, but are extremely difficult to study in the laboratory. The transition for these bands is from a $^1\Sigma$ to $^3\Sigma$ state and is thus forbidden by the spin selection rule. The upper state, therefore, has a very long lifetime (about 1 second) and in laboratory discharges is deactivated by collisions with other types of atoms and molecules and the walls of the discharge tube before it can lose its energy by radiation.

The low spectral resolution that was obtained in the first flight, 17 Å, made it difficult to pick out individual features and assign accurate intensities. As a result, subsequent experiments have been directed toward obtaining improved data in the same wavelength region and the correlation of the various features.⁴

³ H. M. Crosswhite, E. C. Zipf, Jr., and W. G. Fastie, "Far Ultraviolet Auroral Spectra," *J. Opt. Soc. Am.*, **52**, 1962, 643-648.

⁴ R. C. Isler and W. G. Fastie, "An Observation of the Lyman-Birge-Hopfield System in an Aurora," *J. Geophys. Res.*, **70**, 1965, 2613-2617.

The experiment made in February 1965 obtained the very short wavelength ultraviolet spectrum in much greater detail than previous experiments from an Intensity II aurora.⁵ Figure 6 shows a 7.5-second telemetry trace of the far ultraviolet spectrum from 1050 to 1550 Å. Many of the atomic and molecular emissions can be clearly identified. The most spectacular feature of the spectrum is the unresolved 1304 Å resonance lines of atomic oxygen. The 1356 Å lines of atomic oxygen overlap the (3-0) Lyman-Birge-Hopfield band of molecular nitrogen. There are atomic nitrogen lines at 1493 and at 1200 Å. The resonance line of atomic hydrogen at 1216 Å (Ly α) appears, but it is night airglow and not an auroral feature

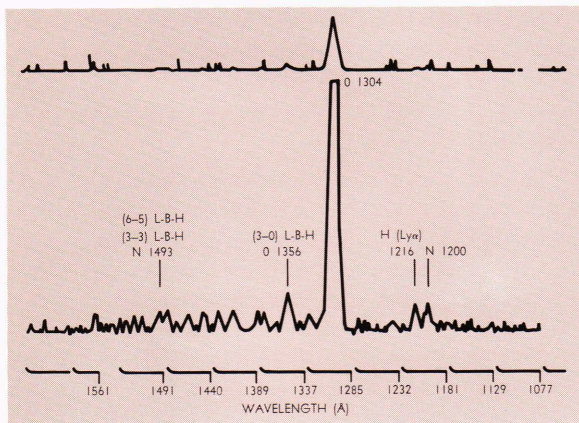


Fig. 6—A more recent far ultraviolet auroral spectrum.

since it remained constant even at peak altitude when the rocket was above most of the active aurora. The rest of the features of the spectrum are bands of the Lyman-Birge-Hopfield system, of which 20 have been identified.

As the rocket ascended, the diffuse aurora cloud in the field of view was remarkably steady and thus it was possible to extract some very significant height profile information.

Figure 7 shows the height profile of the 3914 Å N_2^+ band of molecular nitrogen with the intensity given in kilo-Rayleighs (the brightness unit, Rayleigh is an emission rate of $10^6/4\pi$ photon/ster/sec/cm²). The uniformity of the profile demonstrates how steady was the auroral discharge. This illustration also shows the electron flux curve and the intensity of the resonance atomic oxygen lines at 1304 Å as a function of altitude. The height profile of the 1304 Å radiation is distorted on the low

altitude side by molecular oxygen absorption. On the high altitude side this radiation falls off very slowly. This is not caused by a higher altitude of electron excitation, but rather by the fact that at 1304 Å there are several hundred optical thicknesses of atomic oxygen in the layer, and resonance absorption and reradiation occurs many times before the radiation escapes, resulting in an altitude expansion of the radiation.

Table I gives the intensities of the major features which have been identified from traces such as the one shown in Fig. 6. The calculated intensities for the L-B-H system were obtained by using the appropriate Franck-Condon factors for excitation and radiation and normalizing to the observed (1-1) band at 1464 Å. The agreement between theory and experiment is extremely good for most of the observed bands and for the sum of the observed bands. This calculation indicates that the observed total represents 40% of the energy of the entire L-B-H system and that the entire system is 50% as bright as the 3914 Å band of the 1st negative system (the latter emission is universally used as a standard of auroral brightness).

There were no Birge-Hopfield (B-H) bands of molecular nitrogen brighter than the 50 Rayleigh limit of detection. This result suggests that the brightness of the entire B-H system is less than the L-B-H system (i.e., less than 45% of the 3914 Å band of the 1st negative system).

These results are in disagreement with recent theoretical calculations which predicted that the intensity of the B-H and L-B-H systems would be considerably greater than that which we have

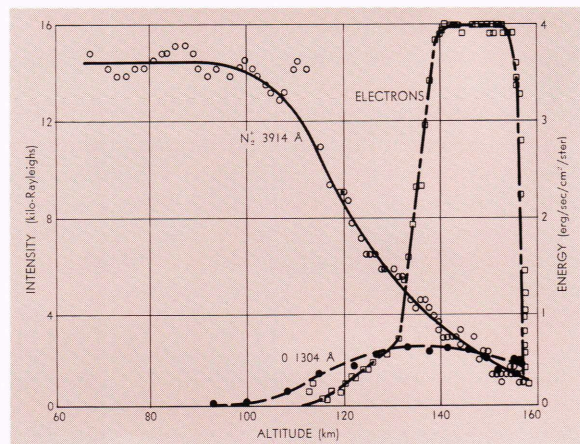


Fig. 7— N_2^+ and O altitude profiles in a very steady aurora. The primary electron flux is also shown. These data show that the aurora electrons do not have a broad energy spectrum. The brightness unit Rayleigh is an emission rate of $10^6/4\pi$ photon/ster/sec/cm².

⁵ W. G. Fastie, R. E. Miller, and R. C. Isler, "Far Ultraviolet Auroral Spectra," Presented at the May 1966 COSPAR Space Science Symposium, Vienna, Austria.

TABLE I
 INTENSITY OF VARIOUS FAR ULTRAVIOLET EMISSION
 FEATURES COMPARED TO N₂⁺ EMISSION AT 3914 Å.

λ (Å)	Identification	Intensity (Rayleighs)		Intensity (kilo- Rayleighs) N ₂ ⁺ (0-0)
		Observed	Calculated	
1200	N	323	—	21
1216	H Lyα	365	—	21
1273	L-B-H (6-0)	100	83	12.6
1304	O	5,100	—	12.6
1325	L-B-H (4-0)	230	278	12.6
1339	L-B-H (5-1)	60	58	12.6
1354	L-B-H (3-0)	490	338	12.6
1356	O		—	
1367	L-B-H (4-1)	40	10	12.6
1382	L-B-H (5-2)	310	54	12.6
1384	L-B-H (2-0)		274	
1412	L-B-H (4-2)	270	137	12.6
1416	L-B-H (1-0)		118	
1426	L-B-H (5-3)	200	36	12.6
1430	L-B-H (2-1)		141	
1444	L-B-H (3-2)	200	115	12.6
1464	L-B-H (1-1)	180	180*	12.6
1473	L-B-H (5-4)	60	53	12
1489	L-B-H (6-5)	380	40	11.6
1493	L-B-H (3-3)		94	
1493	N		—	
1508	L-B-H (4-4)	30	91	11.6
1515	L-B-H (1-2)	60	66	11.6
1523	L-B-H (5-5)	100	8	11.6
1530	L-B-H (2-3)	110	130	11.6
Total for L-B-H bands measured		2,422	2,295	
Total for L-B-H band system			6,300	

* Normalized

measured. Thus it appears that the energy which ultimately ends up in these ultraviolet emitting states is not nearly as much as was previously believed.

In coordination with our 1965 experiment, the Los Alamos Scientific Laboratory conducted a very similar spectrometer experiment at Fort Churchill in a Nike Tomahawk rocket. The Nike was fired 40 seconds after the Aerobee. The two rockets crossed at 125 km, at which altitude the measurements were in close agreement. The Aerobee peak altitude was 160 km, about one-half the peak altitude of the Nike. Thus, for the first time simultaneous measurements at two different altitudes were made in an active aurora. The Los Alamos data confirmed our observation that the Lyα atomic hydrogen was not associated with the aurora. The Nike spectrometer was able to measure the resonantly scattered radiation of atomic oxygen to its peak altitude.

The instrumentation for the February 1966 experiment was similar to previous ones but with the

addition of a secondary electron spectrometer (40 to 900 eV), and a primary electron sensor (>1000 eV) that scanned through 180° of elevation every 10 seconds as the rocket spun about its axis at 2 rps. In this way, measurements of the primary electron flux were obtained over the full solid angle of 4π steradians. Both of these electron detectors were mounted on the ends of 12-inch-long booms which deployed perpendicular to the rocket after the nose cone was ejected.

The analysis of these data is still very incomplete, but preliminary results show that the angular distribution of primary electrons is a maximum at 90° to the earth's magnetic field lines (this closely corresponds to the horizontal plane in the vicinity of Fort Churchill), that the energy distribution of secondary electrons⁶ is approximately exponential over the energy range from 40 to 900 eV, and that there were significant differences in the height profiles of some of the atomic and molecular emissions.

This last rocket carried a more sophisticated payload than previous rockets which we had instrumented and also included experiments from several other universities. In addition to an ultraviolet spectrometer and visible photometer, there was a far ultraviolet photometer (University of Colorado), an infrared photometer (University of Pittsburgh), an electron spectrometer and a spatial resolving primary flux analyzer (The Johns Hopkins University). All of these experiments were designed to make measurements which supported the other experiments on board.

In the future we plan to fly similar coordinated experiments in a cooperative program with other universities, and will fly simultaneously with at least one other rocket which will make measurements at higher altitudes. In addition, we plan to make simultaneous measurements from an instrumented jet airplane which will be able to report on the auroral conditions as they develop to the east and to follow the auroral displays as they move over Fort Churchill.

The auroral displays become brighter and more frequent at solar sun spot maximum, the next maximum occurring in 1970. As our measuring techniques with rocket probes improve and with our growing understanding from satellite measurements of the composition of the solar wind and its interaction with our magnetosphere, we believe that we are on the threshold of solving many of the auroral riddles that exist at the present time.

⁶ J. P. Doering and W. G. Fastie, "Experimental Measurement of Secondary Electrons in an Aurora." (Submitted to *Can. J. Physics.*)