SOME RESULTS OF IGY AND IGC RESEARCH ON THE AURORA AND NIGHT GLOW

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THE International Geophysical Year (IGY) was organized from July 1957 through December 1958 for the purpose of extensive and varied scientific investigations; these investigations were continued through 1959, the so-called year of International Geophysical Cooperation (IGC). All these years were very favorable for research on the aurora and the night glow. Fragmentary results of these observations are now finding their way into print. The many fragments, however, have not yet been compared or unified. The present article is the first attempt in this direction, and covers Soviet research in Loparskaya, Roshchino, and Zvenigorod.[1] The material is divided somewhat arbitrarily into two parts dealing with aurora and night glow. Since the observations were carried out during a maximum of solar activity, the conclusions that follow from these observations will apparently be most characteristic of such a period. More exhaustive conclusions are most likely to be reached after additional investigations are made during years of minimum solar activity.

THE AURORA

Formerly the term aurora was usually used to describe the appearance of some visible luminous formation, for the most part with sharp outlines. However, N. V. Giorgio[2] has shown, by electro-photometric measurements of numerous regions of the sky, that only part of the radiation is concentrated in the sharply outlined brightest formations. In most cases more power was concentrated in the integrated radiation of the surrounding background, which for the most part varied little in intensity, and which was not observed visually only because of the eye's poor contrast sensitivity in poor illumination. The registered ratio of the total radiation power in the background to that in the sharply outlined formations ranges from a maximum of 10 to a minimum of 0.05, the latter being characteristic of only very bright short-lived formations. The polar region of the sky seen in Loparskaya regularly radiated spectrographically-observable emission of the ionized nitrogen molecule even during quiet nights. During the IGY and IGC Giorgio succeeded in observing a northern sky without any additional glow whatever only a few times. However, electrophotometry along the meridian always disclosed an increase in the luminosity of the night-glow emission at heights 100—150 km, starting with the geomagnetic latitude of the center of the aurora zone (67° geomagnetic latitude). The emission intensity in the northern horizon was approximately one and a half times the value at the zenith. If the intensity in excess of that at the zenith could be concentrated at the zenith in an arc one angular degree wide, the arc would be of approximately second category brightness. Some 35 auroras were visually observed in Zvenigorod during the IGY and IGC when the magnetic activity index was $K > 4$. Only 14 of these were photographed with wide-angle cameras, owing to the limited sensitivity. The spectrograph, however, registered 157 cases of increased intensity of the red 6300 A oxygen line. All the foregoing observations were made in clear weather and are thus not representative of the exhaustive statistics of the IGY and IGC period. Owing to poor meteorological conditions and bright nights, it was impossible to observe auroras during 25 magnetically-active nights with index $K > 4$. It must also be mentioned that Barbier[55] and Roach et al[56] observed near the zenith in equatorial regions, in most clear nights, red arcs due to the 6300 A oxygen emission and invisible to the eye. Auroras of low activity are apparently characteristic of all geomagnetic latitudes.

Thus, the concept of "absence of aurora" must be thoroughly reviewed for both high and low latitudes. In light of the foregoing, any set of statistical data on the aurora is meaningful only if intensities and colors are equal. The type of aurora cannot be defined only in terms of its most striking aspect, its form. No less important is the relative contribution that the form makes to the total radiation of the aurora, the degree of development of the brightest most clearly outlined fine formations (for example, elementary rays). In the presence of an aurora the atmosphere is not only optically excited but also ionized. The macroscopic properties of the upper atmosphere, such as the tremendous continuously ionized regions which affect the propagation and absorption of radio waves or the surface electric conductivity which is essential in the formation of geomagnetic disturbances, are characterized for the most part by extensive diffuse fields, rather than by individual isolated formations along the magnetic force lines. Intense geomagnetic and ionospheric anomalies are usually correlated with the appearance of ray-like forms. These forms, however, are not fields of continuous ionization and surface conductivity, so that the true reason for this correlation lies in the accompanying diffuse background of the aurora.

The great abundance of usually unnoticed diffuse auroras produces conditions favoring an appreciable equalization of various types of spectra, since several different formations may lie along the same line of sight. The equalization is enhanced by the scattering of the light in the atmosphere, particularly in the presence of even a slight amount of cloudiness, say cirrus clouds. To arrive at final conclusions it is therefore necessary to employ only material obtained in very clear weather. But equalization is present even under such favorable conditions, owing to the rapid changes in the aurora types and their movement in the sky. Spectrum photographs obtained with long exposures suffer particularly from this shortcoming. If fast recording electrophotometers and spectrometers are used, this shortcoming is reduced, but the spectral distribution of the registered radiation becomes distorted by the rapid variations of the aurora intensity. All the foregoing principal shortcomings prevent us from observing clearcut regularities in the auroral spectra. However, even the disclosure of some tendency or some dependence leads to rather important conclusions.

The hydrogen emission from auroras was usually thought to be the result of direct interaction between the primary protons from the sun and the atoms and molecules in the upper atmosphere, it being assumed that these protons appeared only during major geomagnetic disturbances. Yet, as already reported by V. S. Prokudinova,[3] high-quality spectrographs with dispersion reaching 80 A/mm and resolution reaching 1 A permitted, for the first time in the research on emissions in the upper atmosphere, regular registration of narrow-contour hydrogen emission in the spectrum of the night sky. More details on this emission will be given in the section on night glow. We shall focus our attention here on the fact that Yu. I. Gal'perin, N. N. Shefov, F. K. Shuĭskaya and others[4,5,6,7,8,9] have recorded with high-grade spectographs rather frequent occurrences of the H_α and H_β hydrogen lines with a broad contour that had a Doppler shift in the blue region of the spectrum at the magnetic zenith. The result was a unique collection of spectra with this type of hydrogen emission. When we speak of hydrogen emission in the section on auroras, we shall have in mind only emission with a broad contour.

Gal'perin's observations in Loparskaya have established that in the hydrogen emission from the magnetic zenith the Doppler shift in the short-wave region of the spectrum corresponds to approximately 300—400 km/sec in the region of the maximum intensity of the contour, and can be traced to 1500—2000 km/sec. A certain Doppler shift is also noted in the red part of the spectrum, owing to atmospheric scattering of the hydrogen emission in the direction of the magnetic zenith from the horizontal regions of the sky. This shift increases when the visibility is poor. The most remarkable fact was that in all the types of auroras the main outlines of the hydrogen-emission contour remained the same, accurate to ± 100 km/sec. F. K. Shuĭskaya has established that the situation is approximately the same in Roshchino.

In Zvenigorod, where the hydrogen emission appeared only very weakly in the magnetic zenith, conclusions can be drawn only concerning the contours of this emission from the magnetic horizon. But in this case, too, the data obtained in Zvenigorod, Roshchino, and Loparskaya are in agreement.

The foregoing material enables us to state that the registered radiation is produced by hydrogen atoms with small non-monochromatic velocities. Their velocities differ appreciably from the higher monochromatic velocities of the corpuscular streams from the sun, which are about 10^3 km/sec. The slow radiating hydrogen atoms could result either from appreciable nonradiative retardation of the primary fast protons from the corpuscular streams of the sun, or from acceleration of atmospheric protons due to some interaction between these streams and the outer atmosphere of the earth. Gal'perin[4,5,6,7] made a systematic comparison of the intensities of the hydrogen emissions in the magnetic zenith and on a horizontal wide screen. These intensities were practically always the same, even when some bright aurora formation was located in the zenith. We must conclude from these observations that the field of the hydrogen emission is diffuse, that it occupies a considerable portion of the sky, and that it apparently is not connected or very weakly connected with the sharply outlined brighter aurora formations. The hydrogen emission fields, like the bright formations, move regularly along the magnetic meridian to the south in the evening and return to the north in the morning hours. On the average, the hydrogen emission observed in Loparskaya at midnight was in the southern sky, although it sometimes was seen in the north.

As is well known, Meinel[57] describes the only case when the maximum intensities of the hydrogen and of other emissions have the same zenith angles in a quiet arc near the horizon. In his search for similar data, Gal'perin used exposures up to four minutes and obtained contradictory results. O. L. Vaĭsberg[10,11] therefore repeated in Loparskaya the investigations of the hydrogen emission, using a high-speed recording spectrometer of approximately 10 A resolution, with which a 2000 A spectral interval was scanned 30 seconds at a H_β-line threshold sensitivity of 20 R. The hydrogen emission did not become stronger in any of the bright formations near the zenith. An increase in intensity was observed only occasionally in formations near the horizon, particularly to the south. This, however, could actually be attributed to superposition of more remote high hydrogen-emission fields on the closer and lower fields of other emissions. The increase in the intensity of the diffuse hydrogen fields near the horizon is due to the Van Reyn effect, while the attenuation adjacent to the horizon is due to atmospheric absorption.

We see therefore, first, that no strengthening of hydrogen emission in the zenith formations has been observed up to now and there is no unambiguous convincing proof that such observations have been made in the past; second, stronger emission is observed in formations near the horizon. It would be absurd to assume the second while excluding the first, since this would connect the observer's position with the place where the hydrogen emission is concentrated in the sharply outlined aurora formations. A more likely assumption is that the field of hydrogen emission is as a rule not strengthened in such sharply outlined aurora formations as arcs, bands, and rays. It must be remembered that the diffuse nature of the hydrogen emission fields was a foregone conclusion even earlier, in light of the charge-exchange mechanism of excitation of this emission, first proposed by I. S. Shklovskii.[12] According to this now universally accepted mechanism, the primary protons exchange charges and are excited by collision with the neutral atoms and molecules of the earth's atmosphere. However, once they turn into neutral hydrogen atoms, they cease to concentrate about the geomagnetic force lines as they move downward. It is quite interesting that, according to I. S. Shklovskii, some of the protons turn into neutral hydrogen atoms on their path to the earth while still in interplanetary space.

According to Gal'perin's data, hydrogen emission appears in Loparskaya both prior to the aurora and during any stage of its development. It is sometimes observed even several days in a row, without preferred occurrence at some hour of the day. It is quite remarkable that intense hydrogen emission was often observed in Loparskaya in magnetically quiet days, unaccompanied by any visible aurora formations. In most cases, however, the emission started several hours prior to the occurrence of these formations. In Roshchino and in Zvenigorod the hydrogen emission appeared only occasionally during very strong geomagnetic disturbances. However, both in Roshchino and Zvenigorod, emission was registered simultaneously with many other very strong geomagnetic disturbances. Yet an aurora always appeared at these stations during the time of any geomagnetic disturbance of appreciable size, provided the meteorological conditions were satisfactory, and was observed either visually or with the aid of spectographs, but its spectrum contained no hydrogen emission. According to Gal'perin and Vaĭsberg, the hydrogen fields extend several hundred and sometimes more than a thousand kilometers in longitude, with a maximum intensity on the order of several kilorayleighs. It becomes evident that the total energy corresponding to such extensive emission fields is large. These fields are framed on the north by sharply outlined, mostly mobile aurora formations without hydrogen emission. Observations in southern stations, in turn, show unambiguously that they are also framed on the south by similar formations. In Roshchino, for example, spectrographs registered auroras with emission of the ionized nitrogen molecule in the magnetic zenith 39 times, but hydrogen emission in the magnetic horizon was observed simultaneously only 10 times, while hydrogen emission in the magnetic zenith only three times. Still farther south, in Zvenigorod, the spectrograph registered auroras with emission of the ionized nitrogen molecule 37 times in the magnetic zenith, while hydrogen emission was observed simultaneously only seven times in the magnetic horizon and only once in the magnetic zenith, with very low intensity at that.

The field of the hydrogen emission along the parallels is more or less uniform. It is usually stronger towards the horizon because of the Van Reyn effect. Even though observation of hydrogen emission with a spectrograph is much inferior in resolution to visual and photographic observation of the irregularities in the bright aurora formations along the parallel, nonetheless one cannot fail to notice that the intensity fluctuations seldom exceed 10 or 20 per cent of the mean value, except when due to the Van Reyn effect.

The material obtained by Gal'perin with the aid of spectrographs indicates that hydrogen emission is present most frequently in spectra in which atomic emissions predominate, and is relatively less frequent in spectra with strongly smeared molecular emissions. It is not excluded that in many cases the emission is lost only as a result of strong vignetting, and not because it is functionally absent from the molecular spectra. Vaĭsberg pointed out that during the time of appearance of hydrogen emission the intensities of all the emissions in weak polar auroras are apparently linearly related. We shall see that this feature is inherent in high-altitude auroras and more likely indicates the preferred occurrence of hydrogen emission at high altitudes. Hydrogen emission, however, is not an indispensible component of the atomic spectra, and may be missing from many such spectra.

From his abundant spectrometric material Vaĭsberg's found that in hydrogen emission fields the ratio of the intensity of the Meinel system N_2^2 to the intensity of the first positive system of molecular nitrogen is almost one and half times smaller than in analogous diffuse emission fields without hydrogen emission. On the other hand, a similar comparison shows that the emission of the ionized atom of nitrogen near 5004 A, is one and a half times greater in most cases. This outlines the difference between the auroral spectra with and without hydrogen emission. This is not at all surprising, inasmuch as a similar situation is observed in laboratory spectra.[58] It is difficult to estimate at present the extent to which the emissions produced by protons are vignetted by emissions due to other agents. However, this lack of a clear cut dependence of the hydrogen emission on other emissions in fields with hydrogen emission undoubtedly points to the superposition of emissions excited by different mechanisms. In the extensive material accumulated by Gal'perin with spectrographs and by Vaĭsberg with the aid of a spectrometer it has been established that the spectra of the diffuse visible auroras without hydrogen emission do not differ from the spectra of other sharply outlined formations. We emphasize that we have in mind only auroras in regions of the upper atmosphere not illuminated by the sun. The only exceptions are auroras with anomalously intensified 6300 A oxygen red emission. In such auroras this emission is one order of magnitude and even several orders of magnitude greater than, say the 5577 A green oxygen emission. Such auroras usually have the form of rays, spots, or surfaces whose color is well discerned with the unaided eye. Their spectra will be arbitrarily called the zero type.

All other spectra, regardless of the type of the luminous formations, can be arbitrarily subdivided into three types, although there are no sharp gradations between them. The first type includes those spectra of the night glow in which an intensification of the oxygen red emission (6300 A) by a factor of several times is noticed, together with a nitrogen green emission (5200 A) which is correlated with it. At the same time bands of the ionized nitrogen molecule appear in the ultraviolet region. The type of aurora corresponding to this spectrum is most frequently observed at low latitudes. The second type of spectrum contains many emissions of neutral and ionized atoms, along with traces of emissions of ionized and neutral nitrogen molecules in the visible region. Auroras with such spectra are frequently observed in low as well as high latitudes. The last and third type is characterized by numerous intense molecular bands. It is very remarkable that in such spectra the green 5577 A oxygen emission line and the emissions of the first and second positive and negative molecular nitrogen systems are mutually correlated. An aurora corresponding to this spectrum occurs most frequently in high latitudes.

The difference between the described spectra is apparently connected with the depth of penetration of the exciting agent into the atmosphere. The first type of spectrum corresponds to the highest regions of the atmosphere, where the oxygen and nitrogen are predominantly dissociated. The second type corresponds to regions where the molecular nitrogen content increases, and the third to lower regions, where the nitrogen is in the molecular state. During the time of very low and intense formations, traces of bands of the ionized oxygen molecule appear in the spectra.

To prevent misunderstandings, we must make a few remarks on the lower red edge of the auroras. The traces of emission of the ionized oxygen molecule are very weak and cannot explain the undisputed color of the lower part of such auroras. Since the mean lifetime of the initial state of atomic oxygen for green emission (about one second) is much longer than the mean lifetime of the initial states of molecular nitrogen for the emissions of the first positive system (approximately 10^{-6} sec), the green emission will be unavoidably quenched below 100 km by frequent collisions, just as the red emission of oxygen, with an initial-state mean lifetime of 100 seconds, is quenched in the higher regions. This is well confirmed in the photographs of spectra of the lower boundaries of aurora formations, obtained by Gal'perin at exposures of 10—30 seconds.

The aurora spectra of the molecular type always contain atomic emissions, although of low relative intensity. Sometimes intense auroras with spectra of the zeroth, first, and second type appear above auroras with spectra of the third type, either part of the time (ranging from several minutes upward) or concurrently. Such superstructures are particularly observable in ray-type aurora formations. They offer evidence that the exciting agent penetrates along the same trajectories in both the lower and upper parts of the ray structure, and that the observed intense aurora superstructure is produced only by the less penetrating agent.

Auroras not accompanied by hydrogen emission are undoubtedly caused by electrons. The lower boundary of the aurora indicates the thickness of the atmosphere through which these electrons must pass. Thus, the minimum energy of the electrons penetrating most deeply in ordinary auroras can be estimated at 10 kev or somewhat less. It must be noted, however, that the depth of penetration of electrons with higher energies can be changed by the angle between their velocity vector and the geomagnetic force line. In this case the aurora superstructure can be attributed to anomalies in the distribution of the electron directions relative to the geomagnetic force lines.

V. S. Prokudina,[14,15] N. V. Giorgio,[16] and especially O. L. Vaĭsberg noticed an interesting connection between certain non-forbidden emissions of atomic oxygen and nitrogen, and also the not particularly intense red 6300 A oxygen emission, on the one hand, and the green 5577 A oxygen emission and the emissions of the first and second positive and negative molecular nitrogen systems, on the other. In the spectra of the first type, linear correlation is observed between all these emissions. In spectra of the third type, the intensity of the first group of emissions is less than that of the second group, with a typical increase in the summary intensity of the aurora. All the emissions of the second group are linearly correlated with each other in this case. Although the true values are scattered within one order of magnitude about the mean values, nevertheless the mean ratio of the intensity of the red 6300 A emission of atomic oxygen to the intensity of the 5557 A green line decreases from 5 to 0.05, while the absolute intensity of the 5557 A line increases from 5 to 100 kilorayleighs, respectively.

There are hints that the changes in atomic nitrogen emissions differ from those of oxygen with increasing intensity of the aurora. The spectra of the second type exhibit a behavior intermediate between the first and third types.

Regardless of the cause, detection of a nonlinear relation between the summary intensity of the aurora and the relative intensities of some atomic emissions makes possible an approximate estimate of the surface brightness of the most efficient aurora formations during cloudy weather. This undoubtedly is of great significance for further large-scale observations of auroras. An additional intensity reference can be the sodium emission or the OH bands, which likewise change little during the time of the aurora.

There is no generally accepted explanation for this relation at present. It is not excluded, however, that the mean relative intensities of the oxygen 5557 A green line and of the bands of the first and second positive and negative systems of molecular nitrogen are constant because of the good mixing of the atmosphere, and have therefore a constant relative composition in the region of most intense aurora glow at altitudes near 100 km. In this case, as the stream of corpuscles penetrates downward the number of excited atoms and molecules increases because of the greater density of the atmosphere, but the relative excitation of the different states does not change with altitude. The downward attenuation of the 6300 A line can be attributed to the appreciable increase in the frequency of the de-activating collisions, since the mean lifetime of the initial state is about 100 seconds for this emission. The downward attenuation of the emission of the ionized nitrogen atoms near 5004 A and of ionized oxygen near 8446 A apparently indicates a downward reduction in the degree of dissociation of the molecular nitrogen and oxygen. If we start from these notions, then the greater part of the 5577 A emission produced at low altitudes cannot be excited directly by collisions between the corpuscles and the oxygen atoms. If such a mechanism were to exist, this emission would increase with increasing 8446 A oxygen emission, which is in satisfactory correlation with the emission of the ionized nitrogen atoms produced in the high-altitude region of the practically completely dissociated atmosphere. To reconcile the explanations with the observed picture we must therefore assume that the 5557 A emission is excited at low altitudes principally by collisions between the corpuscles and the oxygen molecules, which causes this molecule to dissociate into an unexcited and excited atom or into a pair of excited oxygen atoms, whereas the 5004 and 8446 A emissions are excited by corpuscles that collide with the atoms of nitrogen and oxygen respectively. In this case the 5557 A emission is less effectively excited than those at 5004 and 8446 A.

It must also be noted that from this point of view the correlation between the 5557 A and 8446 A emissions in the high-altitude spectra of the first type indicates that the relative composition remains constant at high altitudes above 200 km, where the molecules of the atmospheric gas are completely ionized.

As to the persistence of the aurora glow, it must be noted that afterglow is observed only for the low-intensity 5200 A green emission of atomic nitrogen, the 6300 A red emission of atomic oxygen and to a lesser degree the 5557 A green emission. However, the afterglow can be completely reconciled with the mean lifetimes of the states from which the lines originate. No traces of afterglow were observed so far in any of the remaining non-forbidden intense aurora emissions. It is known that the mean lifetime of the recombination glow is determined by the reciprocal of the product of the electron concentration and the recombination coefficient. Since the electron concentration in auroras is usually close to 10^6 cm^{-3}, and the recombination coefficient can hardly exceed 10^{-8} cm^3/sec, recombination glow should have a duration not less than 100 seconds. We can therefore draw the very important conclusion that all the basic strong aurora emissions in the spectral region that is available for observation by modern means appear only as the result of impact excitation by corpuscles and have nothing in common with recombination glow of the ionosphere.

F. K. Shuĭskaya[17,18] observed that the relative population of the upper vibrational levels of the $C^3\Pi$ state of the nitrogen molecule, which are the starting points for the second positive system of molecular nitrogen, increases on the average with increasing latitude of the point of observation. Yu. I. Gal'perin and M. A. Lavrova have shown in addition that in the case of atomic emissions the relative population of the upper levels of the radiating atoms also increases in the mean with increasing latitude of the place of observation.

Since the low bright aurora formations are observed more frequently at high latitudes, and since the higher formations or the tops of formations of high-latitude regions are observed at low latitudes, the conclusion comes to mind either that the less energetic corpuscles predominate in the mean in the locations above the lower regions or above the lower latitudes, or that the energy of the corpuscles increases with decreasing altitude or with decreasing latitude of the point of observation. We have already mentioned the possibility of attributing the superstructures of the aurora formations to anomalies in the angle between the corpuscle velocity vector and the geomagnetic force line, without assuming a change in the hardness of the particles. However, the observed picture does not confirm this assumption, since the upper portions of the aurora are due to a different, softer excitation.

N. V. Giorgio[2,19] established by continuous automatic electrophotometry that the time variation of the 6300 A red emission of atomic oxygen, on the one hand, and of other emissions, on the other, are sometimes in complete disagreement even in time intervals that greatly exceed the mean lifetime of the initial state for the 6300 A emission, i.e., approximately 100 seconds. However, the intensities of all the remaining strong emissions vary in synchronism even within very short time intervals, down to one second for the 5557 A line and over even shorter time intervals for the remaining emissions. During the intense flicker that is most characteristic of the final stage of the aurora, individual, usually non-rhythmic bursts and fadings of radiation are clearly observed, with durations which are sometimes even less than several tenths of a second, separated by considerably greater time intervals. In this case the intensity variations are very complicated in form and, as a rule, nonharmonic. Only when the flicker becomes very frequent is there a hint of regularity. All this indicates that the observed fast intensity oscillations can hardly reflect the harmonic oscillations of the geomagnetic field of the upper atmosphere. As long ago as in 1958 we indicated the possibility of generation of hard electrons through such oscillations of the geomagnetic field.[20,21] However, the material obtained by N. V. Giorgio more likely indicates the opposite, namely the appearance of short-duration variations of this field due to an uneven inflow of corpuscular streams. The short-duration variations of the geomagnetic field and the aurora flicker occur in the final stage of aurora development and do not carry the bulk of the aurora energy or of the magnetic disturbance as a whole. In addition, it is little likely that the energy of the short-duration geomagnetic oscillations could be converted with a high degree of efficiency into the very high kinetic energy of the charged particles.

Since the intensity variations remain synchronous during the flicker time for emissions that have initial levels with greatly different excitation energies, for example, near 4 ev for the green oxygen emission and 20 ev for the bands of the ionized nitrogen molecule, they cannot be due to variations of the corpuscle energy in a range on the order of the excitation potentials of these initial levels. In this case the bursts of radiation from higher levels would be shorter in duration than those from the lower levels, something not observed in practice.

Consequently the modulation cannot be due to the magnetohydrodynamic-wave electrons, whose energies are not particularly high, merely several hundredths or tenths of an electron volt, and which could be suspected of causing the aurora flicker. In principle, two variants of intensity modulation are possible. First, one can conceive of the occurrence of appreciable alternating voltages, which either slow down or accelerate the radiating electrons with energies on the order of several kev. In this case the modulation of the glow would be due to the change in depth of penetration of such electrons, owing to a certain change in the effective cross section for the interaction with the atoms and molecules of the atmosphere. A change in penetration of the corpuscles during the aurora flicker is indeed observed. Since the red 6300 A oxygen emission is quenched more strongly in the denser regions of the atmosphere, one might attempt to explain in this manner certain out-of-phase relationships sometimes observed in the variations of this and other emissions. Second, the aurora intensity modulation could be due to temporary small-scale inhomogeneities in the geomagnetic field caused by magnetohydrodynamic waves or magnetic fields frozen into the corpuscular streams that penetrate into the earth's atmosphere from the outside. Such short-duration geomagnetic anomalies increase the downward dumping of a large amount of geo-active corpuscles from the outer atmosphere. In this case we can conceive of the dumping of not only the continuously penetrating and not too hard corpuscular streams and a reduction in their reflection by the geomagnetic field, but also the dumping of the harder charged particles accumulated in this field. In the latter case, one should expect simultaneously with an increase in the aurora brightness an increase in the absorption of radio waves in the lower part of the ionosphere, for example in the D layer, due to the ionization of the atmosphere by the direct penetration of the highly energetic corpuscles or by x-rays produced at somewhat higher levels when the atmosphere is bombarded with high-energy electrons of several times 10 kev.[22] Inasmuch as the energy carried by the very hard particles from the geomagnetic trap is small, it cannot increase the intensity of the aurora.

The geomagnetic field undoubtedly has inhomogeneities also in the absence of flicker, for example, when moving radiant aurora formations occur. In this case the electric currents of the individual rays produce minute moving magnetic inhomogeneities, which also contribute to the dumping of charged particles from the more remote regions of the geomagnetic field. Sometimes the projection of the radiant arc on the earth's surface becomes sinusoidal. Waves of such a curtain-like band move sometimes in the eastern and sometimes in the western direction, and last several minutes or tens of minutes. When the curtain is near the zenith, usually with corona formations, the moving discrete electric currents in its rays induce stable downward short-duration electric voltages and currents most effectively.

B. P. Potapov, Z. Ts. Rappoport, and T. B. Bortsuk[23] actually observed that intense absorption of 31-Mc cosmic radio emission, which evidences an increase in the ionization of the D layer, occurs when intense moving radiant forms occur at low altitudes in the zenith. The maximum absorption lags the maximum brightness of the aurora in the zenith by 1—10 minutes. Such a lag indicates unambiguously that the aurora-producing corpuscles are not the hard charged particles from the geomagnetic trap that ionize the D layer. An additional confirmation of this fact is that the absorption in the D layer is not so intense in most other aurora formations, except the low moving-ray formations.

Inasmuch as we have considered so far variations of the intensities of emissions not connected with hydrogen emission, i.e., emissions excited by electrons, it would also be of interest to compare the short-duration variations of these emissions with similar variations of the hydrogen emission. O. L. Vaĭsberg made such a comparison and found that the intensity fluctuations of the hydrogen and other emissions do not coincide. This offers additional possibilities of determining the mechanism of the aurora intensity modulation.

The independent behavior of the oxygen 6300 A emission, accompanied in some cases by an intensity increase of several orders of magnitude, has made most attractive the idea of attributing it to the excitation of the oxygen atoms by thermal electrons. T. M. Mulyarchik[24,25,26] ascertained with the aid of an interferometer that the temperature, estimated from the width of the 6300 A spectral line in the region of red formations, actually increases sharply during intense auroras, reaching 3500° K in some cases, whereas in ordinary auroras it is estimated at approximately 1000° K. A temperature increase in the aurora region is deduced also from other emissions produced at lower altitudes, but in this case it does not reach the values typical for the red 6300 A oxygen emission. However, calculations have shown that even an increase in the temperature of the upper atmosphere to the observed temperature is insufficient to explain the observed increased intensity of the 6300 A emission. Gal'perin suggests that this is evidence that the electrons have a higher temperature than the neutral oxygen atoms, i.e., that there is no thermodynamic equilibrium there.

A proof that the upper atmosphere is strongly heated during the auroras is of tremendous significance for the physics of the upper atmosphere. At the temperatures indicated above, the dissipation of neutral atoms and molecules from the atmosphere becomes important. In addition, at such temperatures the ionized particles will penetrate over the entire length of the magnetic force lines and form along them dense fibers of ionized gas. This produces in the exosphere a heretofore unpredicted situation and new conditions both for the propagation of magnetohydrodynamic waves and for penetration of different corpuscles and of external magnetic fields towards the earth. The increase in the height of the homogeneous atmosphere during the auroras explains the existence of long rays with a brightness distribution that is relatively uniform with respect to the altitude.

So far we have considered only auroras that are not illuminated by the sun. However, when the auroras are sunlit, additional very intense fluorescent emissions appear. Like many other investigators, F. K. Shuĭskaya[17,18] determined the vibrational temperature of the fluorescent bands of the first negative system of molecular nitrogen. As in the case when an interferometer was used, she registered a very high temperature in the upper atmosphere during the time of the aurora.

During sunlit auroras, particularly at low latitudes, an upward penetration of fluorescent ionized nitrogen molecules is very clearly observed, first in the form of individual narrow fibers, and then in the form of more extensive formations. This is direct proof of the expansion of the upper atmosphere during the time of the aurora.

The most interesting, however, was the discovery of the infrared emission of helium at 10 830 A, with intensity more than 10 kilorayleigh, in red sunlit auroras. The first report on this emission, without explanation of its still unknown nature, was in a brief communication by A. V. Mironov, V. S. Prokudina, and N. N. Shefov[8] in 1958. At first, however, the single observation of the 10 830 A infrared helium emission was treated with great caution. The most puzzling was the mechanism of appearance of such an emission. Numerous systematic observations made during the last few years by N. I. Fedorova in Loparskaya eliminate any doubt of the reality of this infrared helium emission in red sunlit auroras. Furthermore, N. N. Shefov[29,30] has by now convincingly shown that this emission is due to fluorescence of the metastable 2^3S state of helium in solar radiation. A detailed analysis has shown that the metastable helium atoms can occur in such a state only through collisions between neutral helium atoms in the ground state and electrons with energy of about 25 ev. The region of the red aurora should therefore contain not only many electrons with energies close to 2 ev, necessary to excite the red 6300 A oxygen emission, but also very many electrons with energies close to 25 ev, since the concentration of the helium in the upper atmosphere cannot be too high. It is quite possible that electrons with energies close to 25 ev form an independent group of geo-active corpuscles, causing the red aurora. However, electrons with energies close to 25 ev can also appear in the upper atmosphere as a result of the ionization of the atmosphere, which we have observed with the aid of the third satellite, by strong currents of electrons with energies close to 10 kev.[20,21,31] Thus, the observation of the helium emission under terrestrial conditions uncovers new possibilities for a regular investigation of the helium of the upper atmosphere, and also of strong currents of geo-active electrons. N. N. Shefov developed an exhaustive theory of helium emission and predicted that it should be regularly observed in twilight glow of the atmosphere, although with somewhat lower intensity. In this case, owing to the 537.1 and 584.4 A solar emissions of helium, the singlet states of helium are first excited. The helium atoms in this state are then de-activated by radiation and drop partially to the lowest excited singlet 2^1S state, from which they go to the 2^3S state by collision with the thermal electrons. By now he confirmed his predictions with direct observations.[32] The intensity of the twilight emission of helium reaches 10^3 rayleighs, i.e., this is one of the strongest twilight emissions. P. V. Shcheglov[33] obtained an additional confirmation of this prediction by regularly photographing this twilight emission, in the form of rings, with the aid of photo-contact tubes, narrow-band filters, and interferometers. Inasmuch as the intensity of the twilight emission of helium is a manifestation of the 537.1 and 584.4 A resonant solar helium emissions, the scientific and practical significance of this remarkable discovery to the regular studies of the upper atmosphere and of solar activity can hardly be overestimated.

As is well known, the sides of even lower parts of bright thin aurora rays acquire sometimes an orange color. Although there is no doubt of the reality of this color, it has nevertheless been impossible to obtain by modern means any difference between the spectra of such formations and the spectra of ordinary whitish-greenish rays. In our paper at the 1957 meeting of the Union of Geodesy and Geophysics in Toronto we described this phenomenon as the "weathervane effect."[34] This effect occurs when the corpuscle streams and the atmosphere are in relative motion, it being immaterial which is at rest. When the air is bombarded with the corpuscles, the first to produce visible glow are the low-lag emissions of the first positive system of molecular nitrogen, which have a reddish-orange color (the average lifetime of the initial state is about 10^{-6} sec). However, the glow of the higher-lag 5577 A green emission of oxygen (average lifetime of initial state about 1 second) is delayed by about 1 second. Consequently the portion of the atmosphere crossing the corpuscle beam at the given instant has a reddish-orange color, while the portions that have already crossed the beam are greenish. Owing to the small angular distance between the sides of the moving beam, a distance which cannot be resolved by modern spectral instruments, the difference in radiation is equalized. For example, at an ordinary velocity of the atmosphere relative to the corpuscle beam of about 100 meters per second the distance between the differently colored parts of a thin beam is approximately 100 meters. We have also succeeded in observing many times irregular variations in the beam colors, which evidence a very complicated and entangled circulation of the upper atmosphere, and perhaps even vortical motions. The "weathervane effect" can be clearly observed only when the individual narrow beams are sharply focused, and is difficult to notice in formations that have no clearly outlined boundaries. When the resolution and sensitivity of the recording spectral instruments are improved the "weathervane effect" will offer great opportunities in the investigation of the circulation of the upper atmosphere, since the rate of motion of the corpuscle beam relative to the observer can be determined and then used to ascertain the true motion of the upper atmosphere. Of particular interest is the observation of the "weathervane effect" not only in the green but also in the 6300 A red emission of oxygen, or in the green 5200 A emission of nitrogen, where the average lifetime of the initial state is much longer. In this case different glows can be separated at considerably greater distances.

The aurora photographs in our possession include very strange formations (Fig. 1). These seem to be produced by corpuscle beams passing through clouds of an atmosphere that is more responsive to the corpuscles. Since there were no clouds during the time of the described aurora, there is no doubt that the photographed structure is real. We also found among our collection of photographs many in which the lower parts of all rays of a radiant arc experience a sharp jump in intensity along a common monotonic boundary (Fig. 2). The corresponding auroras were wholly situated in the earth's shadow.

The described aurora formations can be attributed for the time being only to the disorderly or orderly circulation of certain layers of the upper atmosphere, which causes strongly dissociated air with atomic nitrogen, in which no intense molecular emissions can occur, to penetrate downward. Intense molecular emissions appear in clouds or in the lower little-dissociated air which contains a large amount of molecular nitrogen. Since the height of the region where the intensity experiences a jump is always much lower than the height of the homogeneous at mosphere, the corresponding large gradient in the allotropic composition can be maintained only during the time of intense circulation and cannot exist in a quiet atmosphere. Further observation of these modifications of the aurora will apparently make possible further investigations of the circulation and mixing of the upper atmosphere in the aurora zone.

FIG. 1. Aurora in Loparskaya, looking north, 21:00 local time, November 21, 1957.

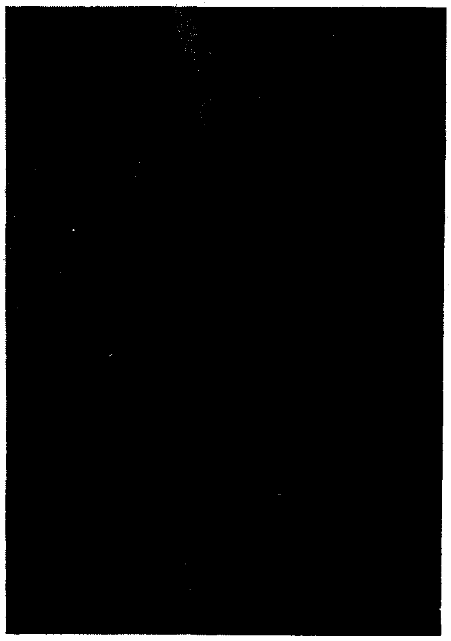

FIG. 2. Aurora in Loparskaya, looking south, local midnight 25–26 November 1958.

We note that the phenomena connected with the circulation of the upper atmosphere do not play an important role in most auroras. The circulation produced by the corpuscles in the upper atmosphere in aurora regions is apparently small. Otherwise the circulation would be readily detected from the intense "weathervane" effect. In principle one can conceive of charged particles being accelerated by the dynamo effect outside regions with corpuscular beams, for example at low latitudes, provided that the only particles participating in this process are those with energies that do not reach the threshold of the excited states from which the emissions of the first and second positive and negative systems of molecular nitrogen start out. We could thus attempt to explain the increased intensity of certain characteristic emissions in auroral spectra of the zeroth and first types, types with no traces of emission of the nitrogen molecular bands. The presence in the upper atmosphere of electrons with energies greater than 7 ev could not go unnoticed, for then the characteristic emissions usually missing from the night glow would appear. The nature of the red arcs in the equatorial region still remains unclear. Inasmuch as magnetic anomalies in the region where the dynamo effect occurs can cause the dumping of charged high-energy particles out of the geomagnetic trap, sattelite observation of such particles above these arcs cannot be regarded as an irrefutable proof against the occurrence of red equatorial arcs via the dynamo effect.[56]

We now mention another phenomenon noticed in Loparskaya during a rapid projection of motion-picture films, and already described briefly in 1957, before the start of the IGY,[22] in our paper delivered to the 1957 Congress of the International Union on Geodesy and Geophysics in Toronto.[34] "In the past years we deduced from visual observations in Loparskaya the existence of large-scale vortical motions of glowing aurora formations. At the end of 1956 we succeeded in confirming this deduction by means of motion pictures taken with 180° cameras. We can even say that before the end of 1956 no other picture of aurora development was observed. The development of glowing formations, usually starting with a quiet arc, follows an ellipsoidal spiral, the major axis of which is hundreds and thousands of kilometers long. The ellipses are stretched out along the magnetic parallel and their minor axes increase with time. In the subsequent stages, radiant forms are produced, which then change into diffuse pulsating auroras."

Sometimes the structure and the brightness of the aurora experience rapid and irregular changes, so that the concentric motion can be discerned only when the motion picture films are projected very rapidly. The motion of the luminescent formation is observed most clearly in radiant arcs with thin rays. Each such individual ray flares up, moves, and is then attenuated. The sharper the focusing of the individual rays, the clearer the picture. The movements have a very complicated and entangled character during the time of magnetic storms. A sharper picture can be traced during short-duration auroras in magnetically quiet days. In the radiant horseshoes, spirals, and more complicated formations the motion is both clockwise and counterclockwise. Sometimes several such formations are observed in a row, with circular motions in different directions. It is quite possible that the curtains are but one modification of motion along a broken trajectory. Sometimes the motion is along a very oblate spiral. When the loop of such a spiral is beyond the horizon, two parts of one loop-like radiant arc may be mistaken for independent formations. In the southern regions, for example in Zvenigorod, no such motions along broken paths were observed. But here, too, both western and eastern motions were observed. It is quite interesting to note that the centers of certain concentrically-moving aurora formations remain in a fixed position for a long time. We refer here, naturally, only to sharply outlined auroras. The diffuse formations that serve as background for these auroras have a more continuous longitudinal structure.

Inasmuch as the overwhelming part of the observed aurora radiation is produced by streams of electrons that are not particularly hard, flowing from the outer parts of the atmosphere, it is possible that the drift of the glowing formations duplicates the drift of these streams in a geomagnetic field that varies in time and in space. The drift velocity reaches a kilometer per second, with the eastern and the western directions equally probable, if the aurora is assigned an altitude of 100 kilometers. Such velocities exceed all possible wind velocities in the upper atmosphere. If such drifting particles pass through the equatorial plane, the drift velocity in this plane is correspondingly greater.

If this is actually a drift of moderate electrons that give rise to the aurora, then it must be noted that this drift does not follow only the magnetic parallels in the eastern direction, as has been recently assumed in analogy with the drifts of the high-energy electrons in the so-called radiation belts. Actually, there is no definite drift direction. The observed picture can be most easily explained by assuming the aurora-producing electrons to drift in arbitrary inhomogeneities present in the external part of the variable (in time and space) geomagnetic field, among which are regions with greater as well as smaller field intensity. Only then is drift in different directions possible. Since the energy of the aurora-producing electrons is about 10 kev and less, some 10 days or more would be necessary before these electrons, located on the magnetic force lines at 67° geomagnetic latitude, could make one circuit about the earth, even in an unperturbed symmetrical geomagnetic field. It is quite obvious that the average easterly shift in a few hours would amount to only several degrees or less. In view of this, the low mobility of the centers of the concentric drift becomes understandable. Electrons that cause any aurora formation whatever spill out much more rapidly than they drift in the geomagnetic field. It is quite obvious that such electrons cannot produce a concentric zone around the earth. They will form during their lifetime only certain fibers along the geomagnetic force line. It is therefore not surprising that the intensity and structure of auroras are quite variable in the longitudinal direction.

Of particular interest is the longitudinal uniformity of the hydrogen emission, which was noticed earlier. An impression is gained that this uniformity cannot be completely due to difficulties in observation and to the diffusion of the hydrogen-emission fields due to proton charge exchange. More precise observations are necessary to clarify this point. It is quite possible, however, that this uniformity is connected with the large drift velocity of the primary protons, if these protons have initially a higher energy than the observed radiating hydrogen atoms. The large Larmor radius of such primary protons could make their drift less dependent on the inhomogeneities of the magnetic field.

In light of the foregoing, it becomes obvious that the radiation belts can be due only to rapidly drifting charged high-energy particles. These particles, however, do not play an essential role in the auroras, since their total power is negligible.

The dimensions of the magnetic-field inhomogeneities that cause the drift of the aurora-producing electrons can be estimated from the dimensions of the aurora loops, shown in Figs. 3 and 4. The dimen-

FIG. 3. Aurora in Loparskaya, looking west, 23:30 local time, 25 November 1958. The projection of the aurora on the earth drifts clockwise.

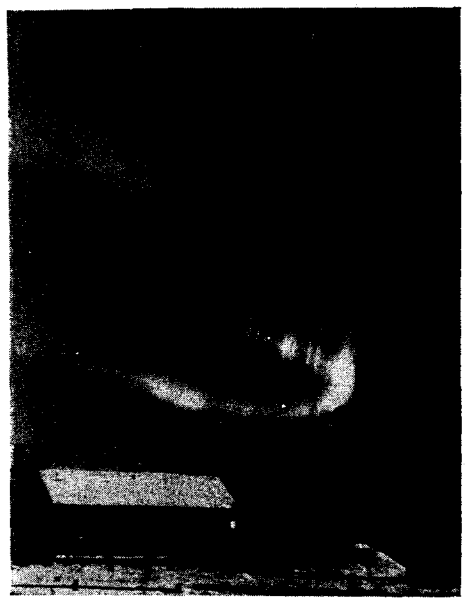

FIG. 4. Aurora in Loparskaya, looking south, 00:30 local time, 26 November 1958. The projection of the aurora on the earth drifts counterclockwise.

sion of the homogeneities will be several times greater in the place where the equatorial plane crosses the geomagnetic force lines from the aurora zone than at the observed loops, i.e., it reaches thousands of kilometers. The very large drift velocity, however, which is many times greater than the drift velocity of the same electrons in an unperturbed geomagnetic field, indicates that the magnetic field intensity gradients are much greater in the inhomogeneities than in the normal geomagnetic field. As is well known,[35] the drift velocity v (cm/sec) in an inhomogeneous field can be given by

$$v \sim E \frac{c}{e} \frac{\nabla}{H^2},$$

where E —electron energy in ergs, c —velocity of light in cm/sec, e —electron charge in cgs esu, H —magnetic field intensity in oersteds (cgs emu), and ∇ the gradient of the magnetic field in oe/cm. With $E \sim 10$ kev, when $v \sim 10^6$ cm/sec and $H - 10^3$ oe in the equatorial plane, we have $\nabla \sim 10^{-12}$ oe/cm. If the inhomogeneity has a dimension of one thousand kilometers, the total change in magnetic field intensity reaches 10^{-4} oe.

Magnetic fields of this intensity, a value predicted previously,[59] have already been registered in corpuscular streams from the sun.[60] Therefore the occurrence of the foregoing inhomogeneities may be connected, as we have already suggested, with the magnetic fields frozen in the primary-corpuscle beams.[21,31] Such fields can also transport from the sun electrons and protons with energies much higher than most particles in these beams. The corpuscle clusters cemented by the magnetic field can apparently explain also the deep penetration in the equatorial plane, near which auroras are now also being observed and where it has become possible to observe at high altitudes, by direct means, not only hard electrons but also more moderate electrons of the same energy as those causing the auroras. Such formations can have a very large "puncturing ability" in a geomagnetic field, since the ratio of their total charge or magnetic moment to the total mass can be considerably less than in the case of individual charged corpuscles. When such a cluster of corpuscles hits the geomagnetic field the kinetic and potential energies of the cluster must be redistributed among all the interacting elements in this field and in the surrounding outer atmosphere. This changes appreciably the energy of the primary corpuscles, and many ions of the earth's atmosphere acquire a high energy, i.e., are themselves transformed into geoactive corpuscles.

The geomagnetic field inhomogeneities that arise in the foregoing processes can hardly be symmetrical with respect to the equatorial plane. Consequently a detailed correspondence between the northern and southern auroras is excluded in principle. Under these conditions, the electrons that produce the aurora need not necessarily oscillate along the force lines of the geomagnetic field from one polar region to the other prior to being dumped completely. This apparently is the case indeed. The inhomogeneous magnetic field need not necessarily belong to the outer atmosphere of the earth, but may be due to the corpuscular streams flowing about the geomagnetic field.

The energy of the electrons that produce the usual low auroras is close to 10 kev. Powerful electron beams with such energies were also observed by us directly at very large altitudes above the zone of the ordinary auroras.[20,21,31] It is quite remarkable and hardly accidental that the protons in the primary corpuscular streams likewise have energies close to 10 kev. On the one hand, this may mean that the protons and the electrons of the corpuscular streams that penetrate into the atmosphere are in energy equilibrium. On the other hand, it is possible that some interaction in the external geomagnetic field causes the protons to lose a predominant part of their energy and to transfer it almost completely to the electrons. It is very interesting that the fields with emission of hydrogen atoms having energies of several hundred ev are bounded on the north and on the south by emission fields excited only by electrons with energies near 10 kev. It is not excluded that this process is connected with the formation in the geomagnetic field of electric fields that ensure transfer of energy from the primary protons to the electrons of the outer atmosphere.

Finally, we can also expect protons and electrons of equal energy to appear in the outer atmosphere as a result of induction processes connected with changes in the magnetic fields of the interplanetary space. In this case, however, the induced electromotive force will have no definite limiting value near 10 kev, and the charged particles can be accelerated to energies both greater and smaller than 10 kev, depending on the rate and amplitude of the change of the external magnetic field.

In connection with the statements just made, attention should be called to the following circumstance. Fine-structure radiant formations are characteristic of moving auroras such as radiant arcs or curtains. The very fine structure of the individual rays, which sometimes reach hundreds of meters in diameter, indicates unequivocably that these rays are produced by monochromatic electrons. The rays would become smeared out were the exciting electrons to have a velocity dispersion and consequently different drift velocities. If the drift velocities of the light formations in the aurora zone range from zero to a kilometer per second, and if the lifetime of the individual rays amounts to several tenths of a second, then the width of the ray should be on the order of several kilometers. The short lifetime of the individual rays is apparently due to the fact that the electron clusters that oscillate along the geomagnetic force lines are much shorter than the external portions of these lines. The mechanism whereby the electrons become monochromatic is still not clear. To gain a better idea of what this may lead to in principle we note that radiant forms usually appear during the principal phase of geomagnetic disturbances, simultaneously with prolonged short-period harmonic variations of the geomagnetic field, which, as already noted, are capable of controlling the dumping as well as the reflection of the electrons. It is quite possible that as they oscillate along the force lines the electrons become sorted out in velocity and are subsequently self-focused in the electrically conducting outer atmosphere, by means of the mechanism proposed by Bennett and Hulbert.[36] The majority of the remaining electrons, which have a considerable velocity dispersion, causes excitation of the more intense diffuse aurora formations. Figure 5 shows the start of a change in the direction of motion of an arc against the background of diffuse

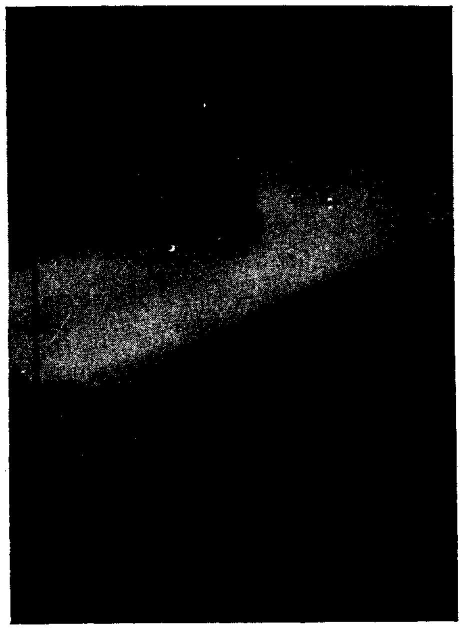

FIG. 5. Aurora in Loparskaya, looking west, 23:30 local time, 25 November 1958. This aurora was the start of the loop shown in Fig. 3. The projection of the aurora drift on the earth is clockwise.

glow, accompanied by framing of the diffuse formations on the north by a radiant arc of very fine structure. The quiet, nonradiant formations occurring during the minimum of solar activity may possibly be due to the fact that the corpuscular streams of the sun are then more uniform, carry frozen-in magnetic field, and are therefore not accompanied by intense short-period variations of the geomagnetic field or by some other processes that cause monochromatization of the electrons that excite the auroras. There is still room here for further research.

The large gap in our knowledge of the aurora is also due to the lack of daytime observations. Having engaged in optical investigations of the aurora, we hoped that radar would provide at least a statistical picture of these phenomena during the day. It was very surprising that the form of radar reflection obtained during the night[37] was not produced by the aurora during the illuminated part of the day. It would be hasty to conclude from this that this means that there are no auroras at all during the day. It would be obviously more sensible to continue with the research and ascertain the cause of this phenomenon. It may turn out that the disappearance of radar reflections during the daytime is due only to a change in the location of the aurora zone, whereby the ionization inhomogeneity geometry that contributes to the reflection is disturbed. This can quite possibly be due to a daytime shift in the aurora zone towards the pole, i.e., in a direction opposite to that at night.

Earth-based observations will not resolve all the problems in aurora research. The daytime picture of the aurora, the detailed structure and location of the streams of protons and electrons that produce the aurora, the origin of auroras, the transformation of the primary corpuscular streams, their initial composition, inhomogeneities, and many other data can be obtained only by direct experiments in the earth's outer atmosphere and in interplanetary space. It is particularly interesting to investigate the uniformity of the drift-current ring in all its portions around the earth. Work in this direction is still in the initial stage of development.

NIGHT SKYGLOW

Proceeding now to a description of the latest data on night glow emission, we must emphasize once more that the line of demarcation between aurora proper and skyglow proper is still uncertain. This uncertainty is particularly great when we deal with the red 6300 A oxygen emission and with the H_α hydrogen emission. Recently hydrogen emission with narrow contour, not wider than 2 A and perhaps even less, was recorded. This does not allow us to suggest that the velocities of the radiating hydrogen atoms are greater than 10^7 cm/sec and that the energies exceed several times ten ev.

N. N. Shefov in our institute and V. I. Yarin in Yakutsk accumulated extensive collections of spectra of skyglow from 3000 to 12000 A.[38,39,40,41,42,43,44,45,46] These contain the lines of the hydroxyl and molecular and atomic oxygen rotation-vibration bands. The total number of resolved molecular band lines reaches 500, in place of the several dozens previously known. The continuous night glow radiation was also registered. It became obvious that in electrophotometry of the night glow emissions it is necessary to take an exceedingly careful account of this continuum in order not to distort the true intensities of the investigated emissions. Flares were also observed in the intensity of the continuum in the blue region of the spectrum. At the same time, Herzberg molecular-oxygen bands also appeared. So far, however, no connection was detected between this emission and other emissions in the night glow.

The reduction of the Zvenigorod data on hydroxyl radiation has shown that the rotational temperature of the hydroxyl bands varies from 200 to 400°K. Very rapid temperature changes, amounting to several times 10°, occur sometimes from night to night. These cannot be attributed to real changes in the temperature of the atmosphere below 100 kilometers, for an impossibly large amount of energy would then have to be absorbed. On the other hand, it appears that the rotational temperature of the hydroxyl reflects the temperature of the surrounding medium. The large temperature changes observed from day to day must therefore be attributed only to changes in the heights of the radiating layers. The temperature differences between bands from different initial levels have demonstrated that the hydroxyl radiation is stratified. It is quite remarkable that the relative population of the different initial levels fluctuates by a factor of several times; this can be explained only by assuming the existence of several, or at least two, mechanisms for the excitation of this emission.

V. I. Yarin obtained in Yakutsk results which are essentially similar. However, whereas in Zvenigorod the intensities of the hydroxyl bands did not seem to depend on the rotational temperature, in Yakutsk, at a temperature above 250°K, there is a clearly pronounced tendency for the intensity to increase with the rotational temperature. The observed increase in the hydroxyl radiation can be attributed to the ozone-hydrogen reaction with approximate activation energy of 3 kcal/mole. A seasonal variation of the intensity and of the hydroxyl-band temperature was observed in Yakutsk, with the maximum values greater during the cold winter time of the year. No such dependence was observed in Zvenigorod. It is thus established that the peculiarities of the hydroxyl radiation depend appreciably on the place of observation.

N. N. Shefov and V. I. Yarin[47] compared all the available material on the temperature of the rotational bands of the hydroxyl and confirmed that this temperature tends to increase with local latitude of the place where the emission is generated. In Zvenigorod, the registered intensity of the hydroxyl bands is not greatly attenuated even during very cloudy weather, indicating apparently that the true intensity increases during that time. By reducing extensive data, the average intensities were determined for all the hydroxyl bands from 5000 to 12 500 A. It follows from these that about 10^{12} new excited molecules of hydroxyl are produced in the upper atmosphere over one square centimeter of the earth's surface per second. The hydroxyl band from the tenth vibrational level was also registered.

N. N. Shefov, V. I. Yarin, and V. S. Prokudina have established[14,15,41,44] that the emissions from the night glow can be divided into two groups. On the one side there is the 5577 A green emission of atomic oxygen, and on the other the following emissions: hydroxyl, 5894 A sodium yellow, hydrogen H_α, and 6300 A red atomic oxygen, all of which are clearly correlated with each other. The correlation is disturbed when galactic fields with hydrogen emission enter into the field of the spectrograph, and when the intensity of the 6300 A red oxygen emission is too high. In all cases a reliable correlation exists between the intensities of the 6300 A red oxygen emission and the 5200 A green nitrogen emission. A. V. Mironov[48] observed that the intensity of these emissions increases with the magnetic K-index.

A very interesting correlation is observed between the hydroxyl and sodium emissions, on the one hand, and the hydrogen and red oxygen emissions on the other. These pairs of emissions are undoubtedly produced at different altitudes, the former pair below 100 kilometers, and the latter much higher. Their mutual relationship can be apparently explained by assuming that the red oxygen and hydrogen emissions are brought about by a single exciting agent, which is effective in the higher layers. The connection between these emissions and the lower ones is apparently due either to a direct downward penetration of the same agent, or to action by this agent through intermediate products that regulate the concentration of atomic hydrogen in the lower levels. It is the concentration of the atomic hydrogen that brings about the intensity of the hydroxyl and sodium emissions. Either electrons with energy close to 10 kev or the hydrogen L_α radiation can serve as such an agent. The active downward-penetrating agent causing the dissociation of the hydrogen molecule may be either the x rays produced when the atmosphere is bombarded by the high-energy electrons or the hydrogen L_α radiation.[22]

It is evident by now that the data on the intensity of the hydroxyl radiation and the data on the concentration of atomic hydrogen below 100 kilometers are incompatible. The number N of newly-formed vibration-excited molecules of hydroxyl above 1 cm^2 of the earth's surface can be written as

$$N_1 \sim h [O_3] [H] \alpha_1$$

in the case of the ozone-hydrogen reaction[49] and

$$N_2 \sim h [O_2^*] [H] \alpha_2$$

in the case of the reaction between vibration-excited oxygen molecules and the hydrogen atoms,[50,51,52] where $[O_3]$ and $[O_2^*]$ — the concentrations of the ozone and the vibration-excited oxygen molecules, respectively, [H] —concentration of the atomic hydrogen, α_1 —coefficient of rate of ozone-hydrogen reaction (according to Bates and Nicolet[49] $\alpha_1 \sim 10^{-12}$ cm^3/sec), α_2 — coefficient of rate of reaction of vibration-excited oxygen molecules with the hydrogen atoms (according to our estimates[52] $\alpha_2 \sim 10^{-10}$ cm^3/sec), and h —height of the homogeneous atmosphere ($h \sim 10^6$ cm). According to Friedman's latest data[53] the concentration of atomic hydrogen somewhat below 100 kilometers barely exceeds 5×10^6 cm^{-3}, and it cannot be greater at lower altitudes, since the atomic hydrogen in the dense layers of the atmosphere rapidly reacts chemically and cannot be found in the free state. In light of all the foregoing, inasmuch as[52] for the vibration-excited hydroxyl molecules $N \sim 10^{12}$ cm^{-2} sec^{-1}, we obtain $[O_3] \sim 2 \times 10^{11}$ cm^3 and $[O_2^*] \sim 2 \times 10^9$ cm^{-3}. Such tremendous values for $[O_3]$ and $[O_2^*]$ are utterly unacceptable. If Friedman's data are not refuted, it will be necessary to seek new mechanisms for the formation of vibration-excited hydroxyl molecules.

The only way out is to assume that the predominant component in the upper atmosphere below 100 kilometers is not atomic hydrogen but its compounds, which are capable of reacting chemically and yield vibrationally-excited hydroxyl molecules. Such compounds are apparently the hydrogen, hydroxyl, and perhydroxyl molecules. The possible reactions are:

$$O_2^* + H_2 \rightarrow OH^* + OH^*,$$
$$O_2^* + OH \rightarrow OH^* + O_2,$$
$$O_2^* + HO_2 \rightarrow OH^* + O_3,$$
$$O_3 + HO_2 \rightarrow OH^* + O_2 + O_2.$$

The asterisk designates the molecules in the vibration-excited ground state. The existence of a free hydroxyl is possible only where the concentration of the atomic oxygen is low and where consequently the appearance of atomic hydrogen in accordance with the reaction

$$OH + O \rightarrow O_2 + H$$

has little likelihood. According to the latest data,[54] the reaction

$$H + O_2 + M \rightarrow HO_2 + M$$

is three orders of magnitude more effective than the reaction

$$O + O_2 + M \rightarrow O_3 + M,$$

where M is any molecule or atom in the upper atmosphere. Consequently, there are substantial reasons for the rapid disappearance of the atomic hydrogen below the 100-kilometer level. At higher altitudes the atomic hydrogen can disappear by upward diffusion and by dissipation. It is also possible that the perhydroxyl is formed in the reaction

$$OH + O_3 \rightarrow HO_2 + O_2.$$

Thus, the excited hydroxyl can occur as a result of various chemical reactions in the upper atmosphere. Each of these will produce its own characteristic relative excitation of the vibrational levels of the hydroxyl. Variations in the heights and intensities of the different reactions will lead to variations in the rotational temperature of different bands and in the relative populations of these levels. This is precisely what occurs in fact.[46] Further research will provide a final explanation for the nature of the hydroxyl radiation.

CONCLUSION

In the course of our investigations we have frequently juxtaposed the intensity of some particular emission with the geomagnetic characteristics. In the mean, a statistical agreement is found. This agreement is fully evident, in particular, when auroras are considered. In many cases, however, there are clearcut disparities, which are not at all surprising. The emissions enable us to observe individual initial elementary processes in completely defined bounded volumes of the upper atmosphere, whereas the geomagnetic phenomena and the macroscopic ionospheric characteristics reflect the summary effects of tremendous spaces, some even beyond the range of visibility from the point of observation. Consequently, a complete and constant agreement between certain variations would appear doubtful. The advantages of geomagnetic and ionospheric observations lies in their complete independence of the time of the day and of the meteorological conditions. But it is difficult to extract from these observations detailed information on the original cause of some particular phenomenon. Observation of the emissions from the upper atmosphere yields direct information on the most basic elementary processes that lead to the formation of the ionosphere and to geomagnetic disturbances. Unfortunately, such observations are possible only during the dark time of the day under good meteorological conditions. It is much more difficult to find a method for observing on earth the emissions of the upper atmosphere during the daytime. However, direct sounding of the upper atmosphere greatly extends the range of possible research on the elementary processes in the upper atmosphere. There are grounds for assuming that in the nearest future it will be possible to clarify many doubtful questions which have thus far remained unanswered.

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[5] Yu. I. Gal'perin, ibid. **35**, 382 (1958), Soviet Astronomy **2**, 351 (1959).

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***By 'Sbornik' is meant here Спектральные, электрофотометрические и радиолокационные исследования полярных сияний и свечения ночного неба (Spectral, Electrophotometric, and Radar Investigations of Auroras and Night Glow) Moscow, Academy of Sciences Press.**

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61