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'AURORAL SPECTRAL VARIATIONS'

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ABSTRACT

A survey is made of the available techniques for studying auroral phenomena, particularly those techniques using ground-based or balloon-borne instruments to detect changes in the auroral particle energy spectrum. From an examination of current knowledge of atmospheric composition and physical processes at auroral altitudes, it is concluded that changes in the auroral particle energy spectrum above about 25 keV may lead to optical spectral changes detectable by measurement of emission intensity ratios or sometimes visually. An examination of colour vision theory at auroral light levels shows that the presence of certain colours in the aurora enables rough estimates to be made of the corresponding emission intensities, and that published luminosity -height profiles for different emissions are probably in error at low altitudes, most likely because of inadequate height resolution.

Wide-angle photometers were designed and constructed to measure emission intensity ratios from balloons in the auroral zone, in an attempt to correlate optical spectral variations with particle energy spectral variations as indicated by the data from accompanying X-ray scintillation detectors. Owing to failure of supporting equipment, no useful data were obtained from the balloon flights, but similar photometers on the ground were operated during

several nights with high auroral activity. Scattered light from extraneous auroral forms interfered strongly with the intensity ratio measurements, but on at least two occasions large increases in the intensity ratio of the N_2^+ 1NG (0,0) band and the $[OI]_{32}$ line were observed, indicating hardening of the auroral particle spectrum, at times when hardening of the spectrum was inferred also from observations of other parameters.

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CHAPTER ONE

INTRODUCTION

The occurrence of auroral displays has been recorded in Western history as far back as 2300 years ago (Aristotle, 340 B.C.), but it is only in the last century that our understanding of the aurora has increased to any great extent. The increasing sophistication of measuring devices and the advent of satellites and rockets have accelerated the accumulation of knowledge so that today the nature of many of the basic processes involved in this natural phenomenon is well established.

An auroral display is now considered to be a manifestation in the atmosphere of the interaction of the solar wind with the geomagnetic field -- Omholt (1965) has suggested the analogy of a scintillation detector for this manifestation. From this point of view the aurora can be regarded as a means of examining the solar wind or of studying the constituents, structure, and reactions of the upper atmosphere. The upper atmosphere may also be used as a large-scale laboratory for testing theories in plasma physics and magnetohydrodynamics, without the perturbing wall-effects of conventional laboratory experiments.

In this thesis we shall consider the aurora from the point of view of studying the reactions occurring in the upper atmosphere, and through this study gaining some knowledge of the properties of the energetic charged particles which are assumed to cause most auroras. Some auroras may be caused by electric fields (Megill and Carleton, 1964), but, in general, most auroral activity seems to be due to electrons of about 10 keV (O'Brien, 1965). Proton excitation may be important south of the auroral zone (Omholt, 1963), but is unlikely to be important in an ordinary aurora within the auroral zone (Chamberlain, 1961, p.252).

One of the salient features of the aurora is its variability, reflecting large changes in the flux, energy, and spatial distribution of the primary auroral particles. Since it is desirable to understand how these changes may be detected, Chapter Two will be devoted to a critical discussion of the various instrumental techniques used in auroral studies, with particular emphasis on those employed in the present work. In Chapters Three and Four a survey is made of current evidence of variations in the energy spectrum of auroral particles, and the effects of these changes are discussed with regard to various methods based on variations in the auroral optical spectrum. An examination is made of the link between absolute emission intensities and emission intensity ratios, on the one hand,

and particle energy spectral changes, on the other. From this examination it is concluded that changes in the auroral optical spectrum, as shown by variations in emission intensity ratios, are valid indicators of changes in the particle energy spectrum.

Chapter Five presents a brief summary of colour vision theory as applied to aurora, in an attempt to ascertain the relation of changes in the observed colour of the aurora to changes in the optical spectrum, and hence to changes in the particle energy spectrum.

Chapter Six gives details of multichannel photometers which were designed to be carried to high altitude by balloons. Owing to failure of other equipment, no balloon-borne results were obtained, but in Chapter Seven some results of ground-based operation of the photometers are presented. The significance of these results as indications of changes in the particle energy spectrum is discussed. Chapter Eight summarizes the main conclusions drawn from the programme, and makes some suggestions for future work.

CHAPTER TWO

REVIEW OF EXPERIMENTAL TECHNIQUES

2.1 GENERAL TECHNIQUES

Experimental investigations of auroral phenomena generally fall into one of three classes:

1) Ground-based observations, which obtain information on the flux, energy spectrum, and spatial distribution of the incident exciting particles by measurements on the auroral optical spectrum or on the magnetic and radio effects of the aurora;

2) Satellite-based experiments, which may use the same techniques as ground-based experiments (e.g. photometry, radio absorption measurements) or may measure the characteristics of the incident particles directly, often some hundreds of kilometres above the visible aurora;

3) Experiments conducted within the atmosphere at high altitudes, this type including rocket experiments and balloon measurements.

2.1.1 Ground-based Investigations

Ground-based experiments include photometric and radar investigations and those using data from such instruments as magnetometers and earth current detectors. Until about ten years ago these were the only ways of studying the aurora. The main advantage of ground work is that the apparatus used can be quite sophisticated, since the restrictions on weight, size, and power are not usually as stringent as for experiments in satellites, balloons, or rockets. There is also the advantage that the apparatus is readily accessible, whether for repairs and maintenance or to check on some unexpected results. One serious problem with ground level photometric observations is absorption and scattering of light by the atmosphere, as well as the effects of cloud and haze. These will be discussed later in this chapter.

Radar reflection methods do not suffer from adverse weather, but the radar reflections are very dependent on irregularities in the ionization pattern and on the geometry of the display, and hence are difficult to interpret (Leadabrand, 1965).

2.1.2 Satellite Experiments

Satellite experiments can measure the parameters of the incident particles directly, and can provide information on auroral forms by recording the luminosity from above either photometrically or possibly, in the future, by television techniques. The high ground speed of a polar-orbiting satellite and the length of time between passes severely limit the usefulness of this technique, since extended observation of the aurora at one point is impossible and differentiation between temporal and spatial variations is difficult.

2.1.3 Rocket Measurements

Rocket-borne instruments can provide measurements from within an auroral display and hence are useful for obtaining data on electric and magnetic fields, luminosity-height profiles and particle energies. The major disadvantages are the short duration of each flight, the complexity and cost of designing and constructing the payload, and the cost of the vehicle itself.

2.1.4 Balloon Experiments

Balloon-borne experiments are conducted at large vertical distances from the aurora but many problems associated with atmospheric absorption and scattering are considerably reduced since balloons can be made to float above 99% of the atmosphere at a pressure altitude of approximately 10 millibars. Thus bremsstrahlung X-rays produced by auroral electrons can be detected for energies above about 10 keV, but most usefully only above 30 keV (Anderson, 1965), and photometric observations are almost entirely free of contamination from atmospheric scattering. In addition, the balloon may stay at operational altitude for periods of the order of a day, or even longer with the use of special techniques. Handicaps include the fact that there is no control over the balloon's course after launch: a high altitude wind of 100 knots (frequently encountered in the winter) can cause the balloon to drift out of telemetry range within three hours. Special care in design and construction is necessitated by the environmental conditions of extreme cold and low pressure. The temperature problem is more severe for auroral balloon experiments than for satellites and rockets, because of the extended periods spent in darkness.

2.2 DISCUSSION OF SELECTED OBSERVING TECHNIQUES

The auroral physics group at the University of Alberta at Calgary has emphasized the study of auroral X-rays by balloon-borne detectors, and the relation of these X-rays to auroral luminosity, radio absorption and geomagnetic activity. Accordingly this thesis will deal especially with balloon-borne and ground-based measurements, with less detailed discussion of the results of satellite and rocket experiments. To do this effectively some knowledge of the usefulness and limitations of the more common methods of observation is required.

2.2.1 Magnetic Field Variations

Variations in the earth's magnetic field can be detected by suitable instruments such as the fluxgate magnetometer. Usually the magnitude in gammas (1 gamma = 10^{-5} gauss) of the field in each of three perpendicular directions is recorded, for example, north (X), east (Y) and vertically downwards (Z) (in the northern hemisphere). Sometimes the three quantities measured are instead the downward component Z, the total horizontal component (H), and the declination (D) measured clockwise from north.

Deviations of X,Y and Z from the quiet-day values are used to specify the geomagnetic 'activity.' If it is assumed that the activity is due to an equivalent straight-line ionospheric current at some point, then the magnitudes and signs of the deviations in X, Y and Z can be used to calculate the direction, distance and relative magnitude of this equivalent current, after corrections have been applied for earth induction effects. The height of the current is usually assumed to be 100 km for computational purposes. Misleading results may be obtained if there are two current systems at different distances or directions and one of these currents dies away or otherwise changes drastically: this might give the appearance of a rapid withdrawal of the current system away from the station. Detection of such false movements introduces undesirable subjective influence in the determination of what is an 'unreasonable' change, which is one of the criteria suggested by Clark and Anger (1966).

2.2.2 Radio Absorption

The riometer (relative ionospheric opacity meter) measures the received intensity of cosmic radio noise, usually at a frequency of about 30 or 60 Mc/s. The cone of acceptance of the antenna is typically one of 30° half-angle, to the half-power point. Suitable electronics and calibration enable the signal at any time to be compared to that during ionospherically quiet periods, and the result is usually given as the absorption in decibels (Little and Leinbach, 1959). The absorption is a function of the amount of ionization in the atmosphere above the riometer, and hence depends on the auroral particle flux. The absorption also depends on the electron collision frequency, and therefore on the height of the ionization, which in turn is dependent on the energy distribution of the incoming particles. Maximum auroral absorption usually occurs in the upper part of the D region (50-90 km) (Heikkila and Penstone, 1962; Brown, 1964), but, depending on the energy spectrum of the incident electrons, maximum absorption may sometimes occur at higher altitudes (Lerfald et al, 1964; Brown and Barcus, 1963).

A significant delay occurs between the onset of an auroral disturbance and the corresponding increase in absorption, which limits the usefulness of this technique in studying rapid variations (Johansen, 1965). Holt and

Omholt (1962) have reported that this delay was of the order of a few minutes for most events, but was rather shorter (less than one minute) in the case of short outbursts of strong aurora.

Another difficulty arises from the fact that the determination of the absorption is essentially a subtraction measurement, in the sense that a patch of ionization, no matter how intense, can cause no more than 50% absorption if it covers only 50% of the field of view. On the other hand, the luminosity associated with this ionization could increase to very large values. Hence studies of absorption/luminosity ratios are strictly valid only for cases when the photometer and riometer fields of view are completely filled by uniform sheets of luminosity and absorption respectively.

2.2.3 Optical Spectral Measurements

Measurements of absolute and relative intensities of auroral spectral emissions commonly employ photometers, consisting of an optical system, narrow bandpass filters, and photomultiplier tubes. Two of the emissions often monitored in this way are the $[OI]_{32}$ auroral green line at 5577A, which is the most prominent visual feature in most auroras, and the (0,0) band of the N_2^+ First Negative system (N_2^+ 1NG) at 3914A, the intensity of which can be readily related to the energy flux required to produce the display (Dalgarno, 1965). The accuracy of absolute calibration of modern photometers from the usual secondary standard source (Shepherd, 1954) is probably seldom better than 10%, but relative intensity measurements can be made more accurately, to about 1% or 2%.

Less recent measurements of spectral features used photographic density measurements to estimate relative intensities and to obtain luminosity-height profiles. While this is still a widely-used spectroscopic technique, it is subject to uncertainty when used for emissions of widely differing wavelengths or intensities, or for emissions of such low intensity that the fog level or the reciprocity failure level of the emulsion is approached, which is quite probable for auroral work.

Ground level photometric observations suffer from atmospheric extinction and scattering even in clear weather. At Fort Churchill and other northerly auroral stations, a large part of this interference may arise from ice crystals in the air (D.J. McEwan, private communication, 1965). Extinction coefficients have been published for a number of wavelengths and zenith angles (e.g. Allen, 1955) but it appears that many auroral workers neglect scattering effects, which may be more important, especially at shorter wavelengths. According to Baum and Dunkelman (1955) scattered light intensity, even under the best conditions, may be twice that predicted by Rayleigh scattering theory, and the extreme variability of atmospheric contamination introduces further uncertainty.

Actual measurements of scattered light intensity under various conditions may thus be more useful, even if only as upper limits, than the uncertain results of scattering theory. Measurements by Boileau (1964) of sky brightness at various angular distances from the sun may be used to estimate the scattered light intensity due to bright auroral forms outside a photometer's field of view, provided some reasonable estimate of the brightness of these forms is known. Boileau's measurements, for a clear day with some low-level haze, showed that the zenith brightness was 3.2×10^3 candelas per metre^2 (cd/m^2) when the sun's disk (6.8×10^{-5} steradian) was at 40-45° elevation. This brightness figure does not change very much for points more than about 15° away from the sun. This compares with a mean brightness of 1.9×10^9 cd/m^2 for the sun's disk (Hughes, 1964). (Hughes also indicates that the average sky brightness in the absence of haze is about 2×10^3 cd/m^2, which is not too different from Boileau's value.) By assuming that the sun has the same energy radiation distribution as a 6000°K black-body radiator (Jenkins and White, 1957, p.432), and that skylight (other than direct sunlight) is produced through

Rayleigh scattering, it can be shown that the contribution of radiation at 5600A to the total measured brightness is only 10% less in skylight than in direct sunlight. (The contributions are respectively about 3.5% and 3.9% for a source of bandwidth 40A centred at 5600A.)

In combination with Boileau's measurements, this result implies that if there is a single patch of aurora which has an elevation of 45° and which subtends a solid angle of 10^{-4} steradian at the earth (i.e. approximately the same angle as the sun subtends) then the brightness of scattered 5577A light in the zenith is 2.2×10^{-6} times the brightness of the auroral patch. For a patch of angular extent 1 steradian, the zenith brightness at 5577A will be about 2.2×10^{-2} times the auroral brightness. Assuming that the scattered intensity at a wavelength λ is proportional to λ^{-4} (as for Rayleigh scattering), the zenith brightness at 3914A will be about 9×10^{-2} times that of the auroral patch. If this patch had a brightness about 50 kR at 3914A and 25 kR at 5577A, the apparent ratio I(3914A)/I(5577A) measured in the zenith under these extreme conditions would be 8:1 rather than 2:1, giving intensities of 4.5 kR and 0.55 kR at 3914A and 5577A respectively, if there were no direct auroral contribution to the signal. In practice, of course, atmospheric conditions will probably be slightly better than those encountered by Boileau, and there will be some direct auroral light coming from the field of view. Also, such a large patch is unlikely to be so bright, and its presence could be easily detected on all-sky camera pictures. Nevertheless, scattered light may sometimes contribute a large error to intensity ratio measurements. This is particularly the case if an auroral form approaches to within less than 15° of the field of view, or if the activity spreads out along the horizon, while measurements are being made on faint aurora in the zenith. Measurements made at large zenith angle are very susceptible to scattering problems, especially in the case of weak aurora or airglow: Barbier and Pettit (1952) discuss an example when the scattered intensity of 5577A at 10° elevation was 9 times the direct intensity. On the other hand, scattering is negligible when all or nearly all of the auroral form falls within the field of view of the photometers, especially at high elevation angles.

The reference to the total inclusion of the auroral form by the field of view seems to imply that narrow-angle photometers are more susceptible to scattering problems, but it must also be remembered that narrow-angle photometers are often steered to make measurements on the brightest part of the aurora, whereas wide-angle photometers are more likely to remain fixed for long periods, regardless of what the auroral distribution is. Also, the viewing efficiency of a steered narrow-angle photometer is greater, in the sense that its field of view is less likely to include large dark areas, while this is almost unavoidable for wide-angle photometers looking at auroral arcs and bands. However, wide-angle photometers are preferable for comparison with other wide-angle devices such as riometers and X-ray detectors, especially when no effort is made to steer the photometers towards the brightest part of the aurora.

2.2.4 Auroral Photography

Photometers of any type can measure only the average luminosity within their field of view; hence one small intense spot cannot be distinguished from a diffuse glow. To obviate this difficulty some means of picturing the sky is necessary. At present this can be done in three ways: by mechanical scanners, by television, or by all-sky cameras. In the work discussed in Chapter Seven, an all-sky camera was used to obtain information on the auroral forms.

All-sky cameras have been used for some decades by meteorologists (Chamberlain, 1961, p.100) and more recently by auroral physicists. A system of convex and plane mirrors enables a 16 or 35 mm camera to record a picture of the whole night-sky, usually at intervals of one minute. The exposure time with films available today is usually about 10 to 15 seconds; exposure and camera operation are usually controlled automatically. All-sky camera pictures are useful for following large-scale motions and fluctuations in the aurora but much finer detail is lost by the poor time resolution. In general no spectral discrimination is attempted other than that afforded by the response of the film.

2.2.5 Auroral X-rays

In recent years auroral X-ray measurements have been made with detectors consisting of a lightly-shielded NaI(Tl) scintillation crystal viewed by a photomultiplier tube. Some form of pulse height discrimination (either in the package or on the ground) is generally used to obtain the X-ray spectrum. Such systems have been described by Pilkington (1965), Anderson (1962), and Brown et al (1963). Geiger counters have also been used, e.g. by Winckler et al (1958) and Bewersdorff et al (1965). While auroral X-rays of energies above 15 keV can be separated from the background radiation by such instruments, atmospheric absorption and scattering at balloon altitudes cause considerable uncertainty in estimating the X-ray production spectrum (Clark and Anger, 1966).

CHAPTER THREE

EVIDENCE FOR AURORAL SPECTRAL VARIATIONS - I: Correlation Studies

3.1 RELATIONS BETWEEN AURORAL PHENOMENA

In spite of much diligent study the relationship between the various auroral phenomena is still not entirely clear. Thus in the case of the association of auroral luminosity and auroral X-rays, as detected by balloons, many workers have reported conflicting results. For instance Winckler and Peterson (1957), Winckler *et al* (1958,1959), and Anderson and de Witt (1963) have reported a close association between the two phenomena; yet on the other hand Anderson (1960,1962) and Anderson and Enemark (1960) found a poor correlation between photometer and X-ray data, as did Barcus (1965) and Rosenberg (1965) using combined photometer and X-ray detector balloon payloads.

The explanation of these conflicting results seems to lie in the changing energy spectrum of the incident exciting electrons and in the fact that a given energy flux will produce very dissimilar effects according to whether it is composed of low energy or high energy particles. This is because different particle energies result in different depths of penetration into the atmosphere and because effects such as luminosity and X-ray production depend differently on incoming particle energies. The most commonly occurring types of aurora have been shown to be produced mainly by electrons (Omholt, 1959; McIlwain, 1960; O'Brien and Taylor, 1964), and the ionization causing cosmic radio noise absorption is also thought to be due mainly to the action of primary and secondary electrons (Gustaffson, 1964; McDiarmid et al, 1961; Rees, 1964). Maximum auroral luminosity usually occurs in the ionospheric E region (90-120 km) while the maximum absorption of cosmic radio noise is usually taken to occur in the D region (50-90 km). Since electrons with energies of approximately 20 keV can penetrate to the 100 km level, while 500 keV electrons are required for penetration to 66 km (Rees, 1964), it is apparent that electrons of entirely different energies may be responsible for the two phenomena at any particular time. Similarly, the total energy emitted as bremsstrahlung by an electron entering the atmosphere is proportional to the square of the initial electron energy (Chamberlain, 1961, p.271), and hence increases rapidly with initial electron energy.

This has some relevance to an apparent association of X-rays with Class b aurora (Sect. 4.1) reported by Pilkington (1965), who found that an X-ray detector flown at Churchill in March 1964 showed several increases in the flux when Class b auroral bands were in the vicinity of the balloon, as indicated by scanner pictures and visual observation. The appearance of Class b aurora can be taken to indicate greater penetration into the atmosphere by the incident primary electrons, and hence a higher energy of these electrons. This would then be expected to lead to an increase in the X-ray flux. An anomalous decrease in the flux occurred at one stage even though the band was brightening, but this may have been due to a decrease in the auroral intensity outside the field of view of the scanner. Energetic electron precipitation at horizontal distances of up to 100 km away from the balloon can be expected to produce some effect in the counting rate (N.R. Parsons, private communication, 1965).

Since satellite experiments (O'Brien and Taylor, 1964; Sharp et al, 1964) have detected large and frequent variations in precipitated electron energy spectra at the top of the atmosphere in the auroral zone, it is perhaps not surprising that the correlation between X-rays, luminosity and radio absorption may at times be rather poor. The variations observed by satellites may be spatial as well as temporal; thus ground observations will not necessarily detect such frequent spectral changes. Results reported by Clark and Anger (1966) show that the X-ray spectrum hardened when the visual northern edge of the aurora passed northward over the balloon, in a manner similar to that observed by satellites during N-S passes over the northern border.

If an electron spectrum change does in fact occur we might expect to find a variation in the ratios of the relative intensities of luminosity, radio absorption and X-ray flux, allowing for the fact that while the X-ray rate and the luminosity are proportional to the flux, the absorption is proportional to the square root of the flux, under equilibrium conditions (Holt and Omholt, 1962). Furthermore we may be able to extract additional information from analysis of the X-ray energy spectrum, or from the luminosity measurements alone if these can be made on two or more emissions excited by electrons of different energies.

3.2 X-RAY SPECTRAL VARIATIONS

Analysis of the X-ray spectrum has been the main tool used in interpreting results from many balloon flights made in the auroral zone in the past decade. A detailed presentation of the theory behind the analysis is given by Anderson and Enemark (1960) who discuss the derivation of the electron spectrum from the X-ray spectrum. However, a useful discussion may frequently be based on only semiquantitative knowledge of the electron spectrum and flux, which is fortunate since there is some uncertainty about the quantitative value of X-ray measurements. Thus results are often quoted in terms of a hardening or softening of the spectrum as shown by the change in ratio between high-energy and low-energy X-ray counts.

Following this approach, Bewersdorff et al (1965) have reported a diurnal variation in the energy spectrum of auroral X-rays in the energy range 20 keV to 150 keV, based on data obtained from balloon flights in northern Sweden. The softest spectra were observed just after local midnight and the hardest apparently about 4 or 5 hours before that, although data on the hardest spectra were scarce owing to the difficulties in having balloons at floating altitude around sunset. These results agree with the satellite measurements of Sharp et al (1965), who found that the energy spectra of precipitated primary electrons on the day side of the earth were generally harder than on the night side.

Bewersdorff also observed rapid fluctuations in the X-ray intensity when the X-ray spectrum was soft. These fluctuations were characterized by changes of factors of 5 or 10 in the intensity and sometimes appeared almost periodic with periods of the order of 6 to 8 seconds. Bewersdorff observed these only between 0000 and 1000 hr local time, and they appeared to be restricted to periods of soft X-ray spectra.

It is thus fairly well established that variations in the X-ray spectrum, in the 20-150 keV region, do occur, showing the existence of variations in the spectrum of the incident electrons in this range. (In being degraded to thermal energies, an electron of N keV gives rise to a triangular X-ray spectrum decreasing linearly from low energies and reaching zero at an energy of N keV.) Since the electron spectrum in this region can vary, it is not unreasonable to expect that variations would perhaps occur in other regions of the electron energy spectrum and furthermore that these variations might be detectable by other techniques. Evidence that this may be the case is available from absorption/luminosity ratio measurements.

3.3 ABSORPTION/LUMINOSITY RATIO VARIATIONS

Johansen (1965) and Ansari (1964) have independently investigated the energy spectrum of the exciting electrons through simultaneous observations of riometer absorption and the 5577A emission. Ansari used narrow-beam antennas, all-sky cameras (ASC) and 5577A photometers at College, Alaska and on the basis of his results concluded that the night-time absorption there fell into two categories: Category 1, occurring at any time from 2000 to 0200 local time, in which there was a good spatial and temporal correlation with luminosity; and Category 2, occurring only after midnight, which had a poor correlation with luminosity and most probably was not limited to luminous regions of the sky. Ansari found that the ratio of absorption to luminosity increased by a factor of 10 in the transition from Category 1 to Category 2. Ansari interprets this as a hardening of the electron energy spectrum and assumes the presence of large numbers of electrons in the energy range 10-20 keV in the first category while postulating large numbers of electrons in the range 30-100 keV in the second category. Category 1 absorption includes that associated with the pre-breakup and breakup phases of the aurora. Variations in auroral intensity during these phases appear to be caused by flux increases alone, with no change in the shape of the energy spectrum.

Johansen (1965) discussed the theory behind combined riometer and photometer observations and also the restrictions on the method in regard to fields of view of the instruments and the absence of quasi-equilibrium during active auroral displays. Working in Norway with apparatus similar in principle to Ansari's he found that the electron spectrum apparently may remain constant for long periods, even throughout a whole night, but that large and rapid variations do occur, though less frequently than would be expected from the satellite observations of Sharp et al (1964).

A statistical average of Johansen's results over three winters showed a diurnal variation in the spectrum with a hardening between 2000 and 0100 hr local time. This behaviour is roughly similar to that found by Ansari. A major difference between Ansari's approach and Johansen's is that Ansari considers that the observed absorption and luminosity in Category 1 events can be accounted for by electrons of 10-20 keV, while Johansen holds that the absorption must be due to a high-energy tail of the spectrum (Johansen, 1965a). Ansari (1965) refutes Johansen's claim that low energy electrons lead to improbable luminosities by a calculation of the expected luminosity from a given energy flux. Recently however Dalgarno et al (1965) have published revised values of the energy flux associated with luminosity and ionization which differ from the older values (Dalgarno, 1965) by a factor of 5. If these newer values based on experimental work are accepted, Ansari's calculations lead to approximately the same result as Johansen's. This seems to show that the absorption is indeed due to a high-energy tail, or at least does nothing to disprove it. Possibly more important here is the fact that long-accepted values for auroral quantities may sometimes be very misleading. This fact is often optimistically ignored.

Ansari (1965) also sought to prove the absence of the high-energy tail by referring to results from balloon equipment (Anderson and Enemark, 1960) and rockets (McIlwain, 1960). This must be treated with reserve since the results in question appear to have an almost unique character (in that very different results have been obtained using the same methods for other auroras), and hence may not apply to Ansari's Category 1. For that matter it is not obvious that the auroral estimates of Dalgarno et al (1965) apply in this case either: they are merely estimates of the average values in auroras. These actual values may differ widely between different classes of aurora.

Ansari's work and Johansen's work suffered from a common drawback: dependence on all-sky cameras for information on the auroral forms during the periods under observation. Hence auroral form variations on a small time scale were smeared out by the poor time resolution of the camera system.

3.4 THE AKASOFU AURORAL MODEL

Synoptic studies of auroral phenomena can be used to build up an auroral model giving a broad picture of the most usual development of auroral activity with time, and providing semantic standardization in auroral descriptions. Furthermore, it is within such a framework that one might look for systematic variations in auroral optical and particle spectra.

A model has been proposed by Akasofu (1964), and developed by Akasofu _et al_ (1965,1965a), to describe several recurring large-scale features of auroral displays. The model holds that the stable form of the aurora is a series of quiet arcs along the auroral zone and that the sequence of events during widespread auroral activity can be described in terms of auroral 'substorms,' each of which comprises an expansive phase and a recovery phase.

During the expansive phase, lasting about 10 to 30 minutes, there occurs a brightening and omnidirectional expansion of a portion of the arc system within about one hour on either side of the midnight meridian. The expansive motion forms an expanding bulge, which if observed before midnight from Churchill (at the northern edge of the auroral zone) should appear as a 'surge' or a mass of light moving from east to west along an arc. Close to midnight, or when the substorm is extremely intense, the surge represents the leading edge of the expanding bulge; surges at other times are merely wavy motions generated by the bulge (Akasofu _et al_, 1965). Weak surges may also be generated by weak activation of an arc, rather than by a large-scale auroral substorm. These weak surges degenerate quickly (in about 10 minutes) and produce little significant magnetic effect. Wavelike motions produced by the expansion may move westward along the arc even after the bulge has passed. Westward surges and bulges are stable and may travel a few thousand kilometres, but the eastward disturbances tend to break-up into patches which drift together into the morning sector. Westward surges often disturb the arc system only temporarily but intense surges may distort the system enough to form complex loops.

Loops are associated with the recovery phase of the substorm when the surges are attenuated and their speed is reduced, giving rise to 'rotational distortion.' Westward loops often travel several thousand kilometres into the early evening before degenerating into irregular bands and quiet arcs. This recovery phase of the substorm may last from one to two hours. During disturbed periods several substorms can occur while an observing station is in darkness, so overlapping of different substorms is possible.

The poleward expansion seen from Churchill around midnight is accompanied by decreases in the magnetic field components, which constitute a 'negative bay,' generally shorter in time than the visual substorm. Intense surges passing overhead sometimes produce a slight negative change in the horizontal magnetic component, followed by a large positive change, or 'positive' bay, but close to the midnight sector the negative bay is more usual (Akasofu et al, 1965).

Surges on the evening side of the earth can be brighter and more active than those on the morning side but the associated changes in the magnetic field and cosmic radio noise absorption are much less significant than those connected with the morning displays. Thus it may be inferred that the electron energies involved in the evening displays are less than 10 keV or so, while the morning ionosphere is bombarded by electrons of higher energies, which will be more efficient in producing absorption effects than in producing luminosity. This conclusion is in agreement with the work of Ansari (1964).

On the basis of balloon X-ray measurements it has been suggested by Clark and Anger (1966) that during the expansive phase the sharp visual northern edge of the aurora, the equivalent line current, and a region of intense X-ray production all move north in unison. During the recovery phase however the line current and the X-ray production region withdraw south again before the visual northern border does, and hence the withdrawal phase might be expected to show a spectral softening as the withdrawal proceeds, after the line current passes southward overhead.

CHAPTER FOUR

EVIDENCE FOR AURORAL SPECTRAL VARIATIONS - II: Assessment of Photon Intensity Ratio Measurements

4.1 CLASSIFICATION OF AURORAL DISPLAYS BY COLOUR

The International Auroral Atlas (1963) distinguishes six distinct colour classes of auroras, denoted by the letters a,b,c,d,e, and f.

Class a: According to the Atlas, Class a includes auroras having red upper regions and green lower regions, where the red is due to the $[OI]_{21}$ (6300-6364A) transition and the green caused by the $[OI]_{32}$ (5577A) transition. This type of aurora was formerly referred to as 'Type A' red, but from Chamberlain's definition of Type A (1961, p.125) it seems that Type A also included what is now known as Class d.

Class b: Class b displays have green upper portions and red lower borders and were formerly referred to as 'Type B.' The green colour is again due to the 5577A line while the red is due mainly to the First Positive band system of molecular nitrogen (N_2 1PG). Dahlstrom and Hunten (1951) detected an enhancement of the O_2^+ First Negative band system in Class b displays, but Evans and Vallance Jones (1965) found that, while some Class b displays showed a 50% enhancement of this system, such an enhancement was not always observed at the time of transition from normal to Class b aurora. Class b aurora is usually associated with intense auroral activity and is thought to occur lower in the atmosphere than other classes. Owing to the short-lived and active character of Class b aurora, however, height measurements on it are quite scarce.

Class c: Class c aurora comprises white, green, or yellow displays. Very faint aurora sometimes appears colourless or white because of the reduced colour sensitivity of the eye at low light levels (see Chapter 5), but more intense aurora may also appear white or yellow instead of the more usual green, due to suitable combinations of green, red and blue emissions.

Class d: A Class d display is one completely dominated by the red OI lines at 6300A and 6364A. This class was formerly grouped together with Class a, and designated 'Type A'.

Class e: Into Class e fall auroral displays which show striated red and green colour, caused by the OI emissions. In this case the division between the colours is not an altitude separation but is probably caused by the differing upper-level lifetimes of the two emissions. These lifetimes are given by Chamberlain (1961, p.579) as 110 seconds for the $[OI]_{21}$ lines and 0.7 seconds for the $[OI]_{32}$ line in the absence of collisional deactivation. This means that if the excitation pattern is moving relative to the atmosphere the red emission will lag behind the green emission, thus causing patches of the two colours (Krasovskii, 1961).

A similar effect may occur (C.D. Anger, private communication) due to the difference in lifetimes of the $[OI]_{32}$ upper level and the N_2 1PG upper level (10^{-6} sec for the latter, according to Krasovskii, 1961). In this case the colour changes will be much more rapid and will proceed in the reverse direction from the effect above, that is from red to green. This kind of display might properly belong to Class b, but no standard assignation appears to have been made.

Class f: Auroras with a blue colour form Class f. According to the Atlas, this class is "commonly dominant" during or after active displays, but at Fort Churchill, at least, it seems to be extremely rare. The blue colour is caused by the N_2^+ First Negative bands at 4709A, 4278A, and 3914A, and is enhanced in sunlit auroras.

Some of the advantages of this classification system are its completeness, since it takes into account all the types of displays that have been reported, and its conciseness, since only a single classification of a display is required, rather than an involved account of its colour. Also, it makes a distinction between completely red auroras (Class d) and auroras with red upper regions and green lower regions (Class a), which were formerly lumped together under 'Type A red!' This distinction is useful since Class d auroras seem to be associated particularly with low and middle latitudes (Vallance Jones, 1965, Dalgarno,1965).

At Fort Churchill, Classes a, d, and f were not observed during March 1965. The most common types were Class c and Class b, with Class e observed infrequently.

Intensities of auroral displays are often stated as International Brightness Coefficient I, II, III, or IV, abbreviated to IBC I, II, etc. IBC I is defined as the brightness of an aurora with an apparent emission rate of 1 kiloRayleigh or 10^9 photons of 5577A per cm^2 (column) per second (Chamberlain, 1961, p.569). IBC II, III, and IV are factors of 10, 100, and 1000 more intense, respectively. IBC I corresponds to about the brightness of the Milky Way, IBC II corresponds to the brightness of moonlit cirrus cloud, IBC III corresponds to the brightness of moonlit cumulus cloud, and IBC IV sometimes is bright enough to cast shadows and to permit the reading of large print. These rough guides are often used to give estimates of the brightness of auroras, but comparison with photometers shows that few observers are able to judge the brightness to better than a factor of five. Diffuse glows in particular often lead to wrong estimates.

4.2 VARIATIONS IN INTENSITY RATIOS OF AURORAL EMISSIONS

Quantitative conclusions concerning the incident electron spectrum are difficult to make since published luminosity-height profiles in general do not show different electron-energy dependence for different emissions. However, since the composition of the atmosphere changes rapidly in the altitude range 80 to 100 km, with virtually no atomic oxygen below 78 km (Spindler, 1965) and an increasing proportion above that level, we would expect that the ratio of intensities of emissions from atomic oxygen on the one hand and those from, say, molecular nitrogen, on the other hand, might vary rapidly with altitude in this region. Changes in the intensity ratios measured from below the aurora should then give a measure of how the electron spectrum is varying, the more energetic electrons possibly giving relatively stronger molecular nitrogen emissions since they can penetrate to altitudes where atomic oxygen is scarce, and where also collisional deactivation of the upper level of the $[OI]_{32}$ line is more important.

To be useful in interpreting ratios in terms of spectral changes the photometer observations should strictly speaking be made in the direction of the auroral zenith, so that information is obtained from one location only, and not from two or more auroral forms at different heights and different distances from the photometers. In the zenith position atmospheric extinction will be less important, and the Van Rhijn effect will be absent. The Van Rhijn effect is the apparent brightening of a luminous layer when viewed obliquely (rather than normally), and results from an increase in the apparent emitting volume.

In general the intensity ratio of the emission at 5577A and 3914A [I(5577A)/I(3914A)] changes very little even when the intensities themselves change by a factor or 100 or 1000. This was first pointed out by Rees (1959) who made observations on low latitude aurora from Fritz Peak, Colorado, by scanning the sky from 10° elevation in the north to 10° in the south using photometers with 5° fields of view. A steady decrease in the ratio occurred during the period 2200 hr to 0400 hr local time but the maximum deviation from this trend was only 50%, which Rees attributed to scaling of the intensity records prior to calculating the ratio. Each scan lasted three minutes, with one minute dark after that, and the ratio after correction seemed to be constant for all elevation angles. The plot of ratio against time was made taking points every four minutes, hence variations on a smaller time scale would not be visible within the scaling error mentioned above. The rather large values of the absorption correction factors (x2 for the 5577A emission at 10°

elevation) illustrate the uncertainties in this type of work.

Omholt (1957) reported an increase in the ratio I(3914A)/I(5577A) towards the upper part of a rayed aurora, the ratio being 20% higher at 60° elevation than at 20°. As Omholt points out, atmospheric extinction corrections for the 3914A emission at the lower elevation angles are not especially reliable, so this ratio change may not be real.

The existence of an altitude variation in the ratios of some emissions is however demonstrated by the occurrence of Class b aurora. Colour vision theory (Chapter 5) indicates that some separation of the profiles of the differently coloured emissions is necessary to explain the vertically separated red and green colours of this kind of aurora. Since the two visually dominant emissions in Class b aurora are the OI 5577A line (green) and the N_2 1PG band system (red), the reddening of the lower border might be due either to an actual increase in the N_2 1PG intensity or merely to an increase in this intensity relative to the 5577A intensity, with no actual increase. The latter effect can be attributed, as mentioned before, to collisional deactivation and the decreased abundance of atomic oxygen at lower altitudes. Neither of these effects will significantly alter the N_2 emissions since

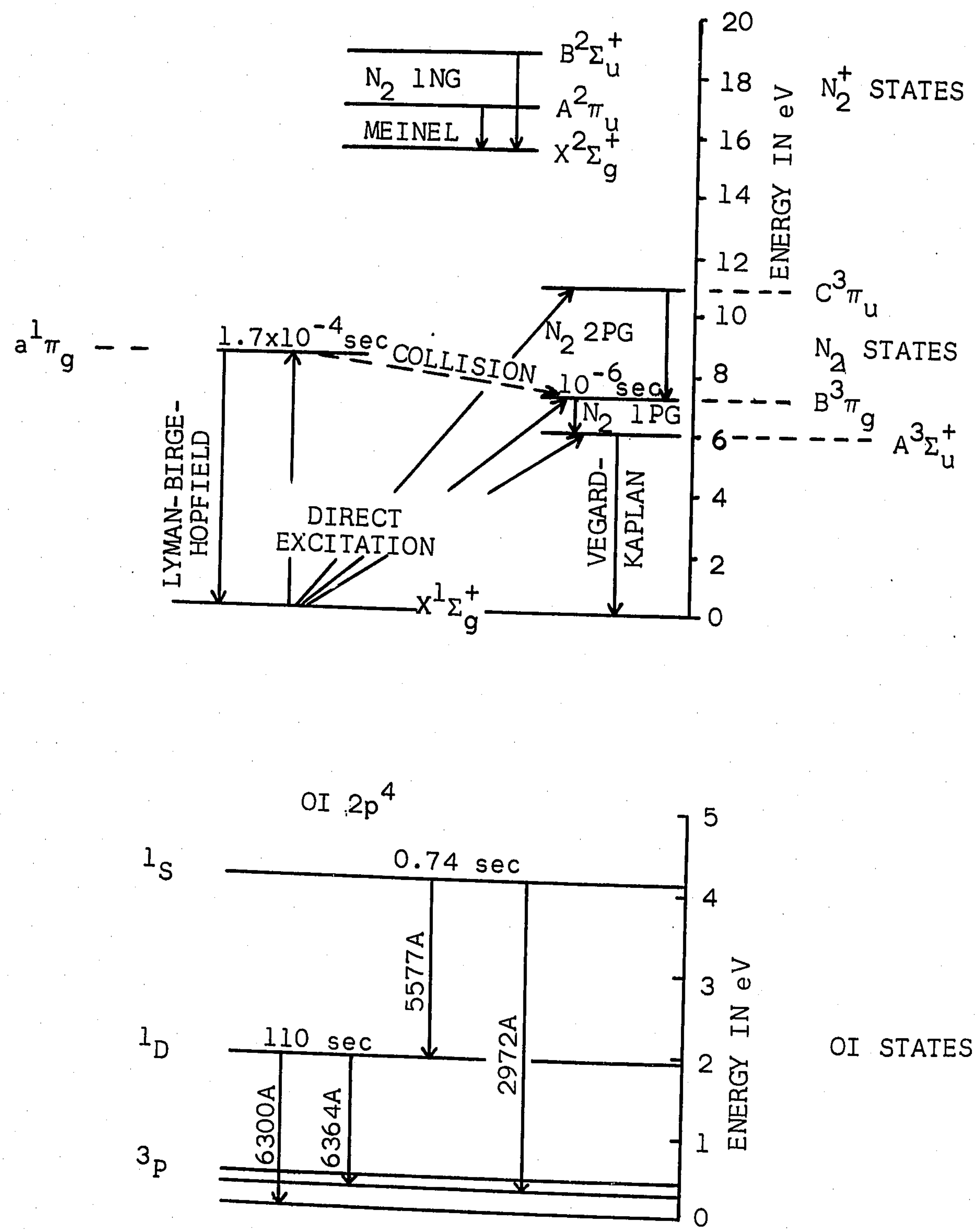


FIGURE 1

ENERGY LEVELS OF OI AND N_2

N_2 is abundant at auroral heights and the lifetime of the N_2 1PG system upper state is much shorter than that of the $O(^1S)$ level according to the results of Evans and Vallance Jones (1965). An explanation of an intensity increase in the N_2 1PG system is given by these authors, after a suggestion by Chamberlain (1961, p.315). This suggestion is that the Thompson-Williams collisional conversion process changes N_2 molecules from the upper state $N_2\ a^1\pi_g$ of the Lyman-Birge-Hopfield system to that of the N_2 1PG system, $N_2\ B^3\pi_g$:

$$N_2(a^1\pi_g) + M = N_2(B^3\pi_g) + M. \quad \text{(Figure 1)}$$

The $a^1\pi_g$ state has a lifetime of 1.7×10^{-4} seconds so that the converting collision must take place,on the average, in a shorter time than this, and hence there would be no time delay in the production of N_2 1PG emission by this process. This is in agreement with the results of Evans and Vallance Jones, but appears to rule out a mechanism suggested by Malville (1959), which would have required a time delay of about 1 second. The Thompson-Williams process would become more effective with decreasing altitude, in agreement with the reported lower occurrence of Class b aurora.

It appears that the ratio $I(N_2$ 1PG)/I(5577A), and to a lesser extent the ratio I(3914A)/I(5577A), will exhibit a dependence on altitude. It follows therefore that these ratios will also exhibit a dependence on electron energy, with harder electron spectra giving higher values of the ratios, provided that our simplified picture of the aurora holds true to a good approximation.

The direct experimental evidence for a height change in the intensity ratios mentioned is rather scarce. This appears to be due to the difficulty involved in making good measurements of luminosity variation with height. With ground-based apparatus the interdependent problems of atmospheric absorption and height resolution interfere with the measurements, and for Class b aurora in particular the rapid temporal and spatial variations do nothing to ease the situation. Rocket observations of horizontal luminosity in isolated arcs appear to be the best way of getting good luminosity-height profiles but to date these measurements have encountered difficulties of their own, caused by rocket spin and precession (D.D. Wallis, private communication, 1965).

The ground-based spectrograms of Class b aurora obtained by Malville (1959) in the Antarctic show the 3914A, 5577A and N_2 1PG emissions peaking at the same elevation angle and tracking each other closely at other altitudes, which would not lead to any change in ratio with height. However, the height profile presented by

Malville is based on only one spectrogram, obtained with a 55 minute exposure of which only the last eight minutes involved a Class b form. Other reported forms in the field of view during the earlier 55 minutes almost certainly contaminated the results.

Evans and Vallance Jones (1965) reported changes in the intensity ratios of the 3914A, 5577A, and N_2 1PG emissions when the aurora changed from Class c to Class b. These measurements were made at an elevation angle of 30° or less and so do not yield information on the incident electron spectrum over a vertical column. To eliminate the effects of atmospheric absorption and the associated correction uncertainties, the direction of the photometers was fixed while making the comparison between the two types of aurora. If Class b aurora does occur lower in the atmosphere than Class c then it is possible that these measurements actually compared one auroral form with another which was both further away and, more important, higher in the atmosphere. From the observed ratio changes we then in fact obtain a two-point estimate of the luminosity profiles telling us that a point lower down on a Class b form has a greater proportion of red than a point higher up on a Class c form under the same viewing conditions. From this we cannot say whether or not the electron spectrum has steepened, but it does serve as an indication that the red and green emissions do not have the same luminosity-height profiles.

Further possible evidence of a profile separation is provided by statistical analysis of heights of auroral lower borders in terms of frequency of occurrence. Results obtained from large numbers of auroras by parallactic photographic methods show a definite double peak in the height-frequency plot, at altitudes of about 100 and 108 km (Harang, 1951; McEwan and Montalbetti, 1958). Division of the auroras studied into groups of varying intensities shows that the lower peak is associated with stronger auroras. Chamberlain (1961, p.129) discounts the suggestion that the double peak is due to tidal oscillations in the atmosphere but gives little indication of an alternative cause. Certainly there seems to be no statistical explanation for obtaining such a bimodal plot from the unimodal grouping that would otherwise seem 'natural.'

A possible explanation is that 'strong' auroras are different in some respect from medium and weak auroras as far as photographic detection methods are concerned. None of the experimenters quoted gives any indication of the distribution of colour class of the observed displays, although during the observations of McEwan and Montalbetti Class b aurora was extremely rare (D.J. McEwan, private communication, 1965). However, the appearance of a secondary lower peak with increasing intensity might be due to the lower peak's being composed of red emissions while the upper peak consists of green emissions. The response of most photographic materials, except that of special infrared emulsions, is much less for red light than for green light; this fact, coupled with the lower intensity of the red emissions relative to the green line, could result in reciprocity-failure in the detection of red emissions in the case of weaker auroras but not for more intense displays. Such a conclusion would imply, that, at least in some cases, the location of the photographic auroral lower border would be determined by an atmospheric process rather than by any sharp altitude cut-off in the incident particle flux. The height resolution of the emission profile measurements made by Evans (1963) was of the same order as the separation of the two peaks mentioned previously, and his measurements cannot reliably prove or disprove the existence of the peaks.

The simplest and most obvious proof that the green/red ratio does change is that afforded by the visual appearance of a Class b aurora. Chapter 5 therefore examines the predictions of colour vision theory on the advantages and disadvantages of the human eye used as a detector at auroral light levels. Some knowledge of these capabilities and drawbacks is important since auroral observers are rarely strong-willed enough to refrain from looking at the aurora directly and the apparently obvious conclusions thereby drawn may be quite erroneous. In addition of course the human eye still has advantages over present-day instruments in visual resolution and wide field of view, as well as being remarkably sensitive for such a compact device.

4.3 UPPER LEVEL LIFETIME EFFECTS

The prominent auroral transition $[OI]_{32}$ at 5577A, being strictly forbidden by electric-dipole radiation, is possible only through the existence of electric-quadrupole radiation (Chamberlain 1961, p.580). The resulting small transition probability gives the ^1S state its lifetime of 0.7 seconds, since the only other transition $[OI]_{31}$ is even weaker. On the other hand the N_2^+ 1NG (0,0) band at 3914A has an upper level lifetime of 10^{-8} seconds (Chamberlain 1961, p.439). We thus expect that if the auroral atmosphere were subjected to a very short spike of exciting electrons then the resulting 3914A emission would decay in about 10^{-8} seconds, but the 5577A line would take about 1 second to decay. In the case mentioned the maxima of the two emissions would occur at the same time at the trailing edge of the spike, but in practice a time lag is often observed because the electron burst is of finite duration and has a finite rise-time and decay-time.

The equation governing the time rate of change N' of the population N of the upper level is

$$N' = Q - N/T \qquad (1)$$

where Q is the rate of excition and T is the lifetime of the upper level. T is related to the transition probabilities A_{mn} of all transitions from the upper level (m) to lower levels (n) and to the collisional deactivation probability d by the equation

$$1/T = \sum_n A_{mn} + d. \qquad (2)$$

For the $[OI]_{32}$ upper level this becomes

$$1/T_O = A_{32} + A_{31} + d \qquad (3)$$

where A_{32} is 1.28 sec^{-1} and A_{31} is 0.078 sec^{-1} (Chamberlain, 1961, p.580). The quantity d depends on the total particle number density, and therefore, in an aurora, d depends on the altitude of emission. Because of the short lifetime of the upper level of the 3914A band the emission intensity is proportional to the rate of excitation. If the rates of excitation of 5577A and 3914A upper levels are assumed proportional by a constant k then we can say for the $O(^1S)$ state that

$$Q_O = k\ Q_N \quad \text{and} \quad Q_N = I_N$$

where Q_O, Q_N refer to the rates of excitation of 5577A and 3914A upper levels respectively and therefore

$$N_O' = kI_N - N_O/T_O \qquad (4)$$

where I_O is the photon intensity of the 5577A line,

I_N is the photon intensity of the 3914A band,

and N_O is the population of the $O(^1S)$ state.

Thus if we let $I_O' = dI_O/dt$ we can write

$$N_O' = kI_N - I_O/A_{32}T_O = (1/A_{32})I_O' \qquad (5)$$

since

$$I_O = A_{32}N_O. \qquad (6)$$

Defining K to be $A_{32}T_Ok$ we can rewrite Equation (5) above as

$$KI_N = I_O + T_OI_O'. \qquad (7)$$

When I_O' is zero, or when T_O is zero, K gives the ratio of intensities of the 5577A line and the 3914A band. The actual ratio at any time is

$$K' = \frac{K}{(1 + \frac{T_OI_O'}{I_O})} . \qquad (8)$$

Omholt and Harang (1955) were the first to develop and use this theory to obtain measurements of T_O from the aurora. Their maximum values for T_O were in agreement with the theoretical values of Garstang (1951). The lower values of T_O ranged down to 0.45 seconds, this decrease being attributed to collisional deactivation. The analysis was performed on 3914A and 5577A records from active aurora chosen so that I_O' was as large as possible. For each segment of the trace selected, usually about one or two seconds long, time-integrated values of I_N, I_O and I_O' were computed to give a linear relation between K and T_O in an orthogonal K-T coordinate system (Equation 7). When several such relations were obtained and plotted, the intersection of the straight lines gave the mean effective values of K and T_O. The relations could have been solved analytically by the method of least squares, but Omholt and Harang preferred to use a graphical method, which gave a visual indication of the scatter in the value obtained. The uncertainty in the K value obtained is much less than that in T_O: this is because I_O' is usually not very large and hence the slopes of the various lines are not greatly different from zero.

This same method has been used by many workers to obtain values for T_O in different types of auroras, e.g. by Evans and Vallance Jones (1965), and Daniels and

Newman (1965). Essentially the same method was used by Paulson and Shepherd (1965) but their experimental technique was different and their analysis more sophisticated. Instead of restricting themselves to active auroras they measured very small fluctuations from visually quiet auroral displays and performed cross-spectral analysis on the associated 3914A and 5577A variations. Less subjective bias is introduced this way and more efficient use is made of the data.

Paulson and Shepherd used the deactivation coefficient value obtained for atomic oxygen in a laboratory by Barth and Hildebrandt (1961) and from it estimated the height at which the fluctuations occurred. They obtained reasonable results from their own measurements, and a similar analysis of the published figures of Evans and Vallance Jones from Class b auroral displays gave height figures of around 85 km, in agreement with the generally accepted value for this class of aurora.

In spite of this seemingly consistent picture there appear to be some flaws in the analysis of Omholt and Harang, most probably in the initial assumption of constant k and in the assumption that T_O remains constant over the period of each data sample. This is shown by the relation between K/T_O and T_O plotted by Omholt (1955). From his published values it appears that this relation is almost hyperbolic, i.e. K remains almost constant as T_0 changes. When T_0 decreases from 0.81 to 0.45 seconds K decreases by only 7.5%, from 0.49 to 0.45. Evans and Vallance Jones obtained values for T_0 of 0.45 seconds for Class b aurora, so from Omholt's work a change in K of about 10% at most is all that could be expected in going from a Class c aurora to a Class b aurora. This is not in agreement with the actual ratio changes of up to 38% obtained by Evans and Vallance Jones.

4.4 EFFECTS DUE TO VARIATION IN ATOMIC OXYGEN CONCENTRATION WITH HEIGHT

Since K ($= A_{32}T_0k$) decreases by 7.5% while T_0 decreases by 40 to 50% (previous section), it follows that the product $A_{32}k$ must be increasing and so tending to cancel out the decrease in T_0. A_{32} is a quantum-mechanical constant, therefore the increase in $A_{32}k$ implies that k increases as T_0 decreases, that is, at lower altitudes relatively more oxygen atoms than nitrogen molecules are being excited to the 5577A and 3914A upper levels, respectively, than at higher altitudes. This could occur through a change in the excitation mechanism of either level, probably of the $[OI]_{32}$ upper level. This cannot be ruled out, but, as will be shown, the change would have to be one involving a drastic change in the excitation efficiency.

Even if the excitation mechanisms remained unchanged, it might be said that k could increase if the distribution of active electrons (i.e. electrons capable of causing excitation) shifted so as to give a greater abundance of electrons in the 2-15 electron-volt region, relative to the abundance of electrons with energies about 15 electron-volts. Since the energy of the $[OI]_{32}$ emission is 4.17 eV, while that of the 3914A emission is 18-19 eV, this change in the active electron distriubtion might be expected to increase the intensity of the $[OI]_{32}$ emission relative to the 3914A emission, simply because many of the electrons could excite the oxygen emission but not the nitrogen one. However, the relative abundance of the electrons at the lower altitudes in the 2-15 eV energy range will in fact be diminished (rather than increased), by inelastic collisions with N_2 molecules, and the net effect is probably the suppression of the 5577A line, instead of its enhancement (Chamberlain, 1961, p.310).

At any rate, Omholt's relation between $A_{32}k$ and T_O shows $A_{32}k$ increasing down to T_O values of less than 0.3 seconds. From the results of Spindler (1965) and Barth and Hildebrandt (1961) (see below) it appears that such low values of T_O imply an altitude of emission (82-85 km) where the abundance of atomic oxygen, relative to that of molecular nitrogen, has fallen to about one fiftieth of its value in the 95-110 km region. This in turn implies that the proportion of atomic oxygen atoms being excited at 82-85 km is about 100 times greater than that at 95 km, if we assume that Omholt's findings are reliable and that the mechanisms of excitation of OI and N_2 do not change in this height interval. The latter possibility cannot be ruled out, but the change would have to be rather drastic to achieve such a large increase in the rate of excitation of oxygen atoms.

In any case, large changes in K can clearly occur, as evidenced by the results of Evans and Vallance Jones and the results of Chapter 7, but Omholt's analysis is not strictly applicable unless k and T_O (and therefore K) remain constant during each interval for which they are computed. It is true that Evans and Vallance Jones concluded that their observed ratio change could be accounted for by collisional deactivation, but their calculations took no account of a possible change of k with T_O. The relation found by Omholt (1955) casts doubt on the theory that the decrease in the 5577A intensity is due mainly to deactivation. Examination of recent experimental measurements at auroral altitudes supports the view that atomic oxygen concentration is a more important factor. Such measurements are those of Spindler (1965), Golomb et al (1965), and Halliday (1960).

Spindler (1965) released nitric oxide from a rocket in the 100 km region and measured the brightness of the chemiluminescent reaction of nitric oxide with atomic oxygen:

$$NO + O \rightarrow NO_2 + h\nu.$$

From this he was able to make a rough determination of the atomic oxygen concentration C_O as a function of altitude. On all three of the flights conducted over Churchill the peak C_O was at 96 km and no atomic oxygen was detected below 78 km. This latter results is an important addition to upper atmosphere knowledge: before these flights, direct C_O data were available only for heights above 100 km (by mass spectroscopy) and such a model atmosphere as that quoted by Chamberlain (1961, p.576) appears to be quite wrong in the C_O values below 100 km.

There is evidence for a dependence of the height of the atomic oxygen layer on latitude. Spindler's Flight 3 was made after dusk at Wallops Island, Virginia (49 °N geomagnetic latitude), where the peak of the C_O profile was at 102 km, while the profile shape was roughly the same as at Churchill. Golomb <u>et al</u> (1965) working at Eglin Air Force Base, Florida (40 °N geomagnetic latitude), found the C_O peak there to be in the 103-107 km region during the three flights which they made. (They also

TABLE 1 - Variation with altitude of some parameters affecting I(5577A)/I(3914A)

Altitude (km)	Electron Penetration Energy (keV)	Atomic Oxygen Concentration C_O (cm^{-3}) normalized to 100 at 96 km	Molecular Nitrogen Concentration C_{N_2} (cm^{-3}) x 10^{11}	$\frac{C_{N_2}}{C_O}$ normalized to 1 at 115 km	Percentage reduction in 5577A intensity due to deactivation of the $[OI]_{32}$ upper level
80	150	6	3470	620	60
85	90	25	1120	48	30
90	50	58	350	6.6	15
95	25	100	120	1.3	9
100	17	75	42.5	0.61	5
105	10	30	15.5	0.55	3
110	8.5	9.4	8.1	0.93	1
115	6	2	1.85	1	0

The electron penetration energies for the various altitudes are taken from Rees (1964); the C_O values are taken from Spindler (1965, Flight 7); the C_{N_2} values are taken from Chamberlain (1961). The quantity in the last column was calculated using the results of Barth and Hildebrandt (1961) and the total particle number density from the model atmosphere given by Chamberlain (1961).

found that there was little difference between the day and night values of C_O.) Since the height of the C_O peak was 96 km at Churchill (69°N geomagnetic latitude), these results seem to indicate that a 10° increase in geomagnetic latitude leads to 3 km decrease in the altitude of the C_O peak. In this height region an altitude change of 10 km changes the particle number density by a factor of 7 or 8.

The numerical value of the effect cannot be considered reliable until a great many more determinations are made, since the flights mentioned took place at varying times and dates. However the probable existence of this latitude variation indicates the need for caution in using measurements made at one latitude to calculate an expected effect at another latitude.

4.5 RELATIVE INFLUENCE OF ATOMIC OXYGEN CONCENTRATION AND COLLISIONAL DEACTIVATION ON $[OI]_{32}$ INTENSITY

If we accept Barth and Hildebrandt's value (1961) of 4.5×10^{-15} cm^3/sec for the atomic oxygen deactivation coefficient, and Spindler's Flight 7 profile for the post-dusk C_O above Churchill, it appears that the fall-off in C_O with decreasing altitude is more important in diminishing the 5577A intensity than deactivation of the excited atom could be (Table 1). If the results of his other flights are used the effect is shown even more strongly.

From 100 km to, say, 150 km the concentrations of molecular nitrogen and atomic oxygen are roughly proportional, at least to a factor of four, but below 95 km the N_2 concentration increases steadily while C_O falls off rapidly. The ratio of the N_2 concentration to that of atomic oxygen is five times greater at 90 km than at 95 km, while at 85 and 80 km the ratio is respectively 37 and 480 times greater than at 95 km (Table 1). The rate of direct excitation from the N_2 and OI ground states should be roughly proportional to the respective concentrations of N_2 and OI, and therefore we would expect corresponding changes in the relative intensities of nitrogen and atomic oxygen emissions.

On the other hand, deactivation of the $O(^1S)$ state is negligible at 115 km and above, but at 100 km it will produce a 5% decrease in the 5577A intensity, while at 90 and 80 km (Table 1) the corresponding decreases from the 115 km value will be 15% and 60%. The 80 km value corresponds to a decrease of 55% from the 95 km value. The change in C_O in going from 95 to 80 km is clearly of greater importance than the change in deactivation, since it leads to a change of a factor of 16 in the ratio I(3914A)/I(5577A), compared to the factor of two given by deactivation.

The above conclusions are supported by the work of Halliday (1960) on the 5577A line in meteor wakes observed at Meanook, Alberta. The extreme height range of the emission was from about 120 km to 79 km, the lower heights showing some association with increased solar activity, although the number of observation (8) is not sufficient to be conclusive. Photographic spectral records obtained using a rotating shutter indicated that de-exciting collisions were less frequent than 5 per second even at 80 km. Five collisions per second would reduce the intensity at 80 km by 80% of the undisturbed value. Halliday therefore concluded that the disappearance of the 5577A line below 79 km was not due to deactivation, but must occur 'because some necessary reagent was no longer present.' Halliday's conclusions on the height of emission, the numerical value of the frequency of de-exciting collisions, and hence the role of deactivation in diminishing the emission intensity, are thus in good agreement with those given in Table 1, based largely on Spindler's results from a different technique.

It is significant that there appears to be no evidence from Halliday's work that strong 5577A emission occurs below the assumed lower altitude limit of the atomic oxygen concentration. This might be taken as showing that mechanisms of excitation, other than direct excitation of oxygen atoms from the ground state, are not important in meteor trails. While this does not rule out the possibility of such mechanisms being important in aurora, it definitely seems to decrease the probability of this being the case, and hence casts doubt on the increase in the rate of excitation of atomic oxygen (relative to that of molecular nitrogen) reported by Omholt (1955) and discussed in Section 4.3 of this thesis.

Some discussion of the apparent excellent height agreement between the results of Spindler and Halliday is in order. Halliday worked at Meanook, which is about 7° magnetically south of Churchill, where Spindler's results were obtained: the latitude effect would probably lead to a difference of 2-3 km in the height of the atomic oxygen lower border, Meanook being expected to show a higher altitude. In fact Halliday's lower limit was 1 km higher than Spindler's. An important point is that Halliday does not give an uncertainty estimate for his height values, and it is difficult to estimate the height uncertainty from his paper. He calculated the heights by measuring the angular velocity of the meteor at some point on its trail and assuming accepted values for the speed of the meteor shower in question (this is probably accurately known: cf. Evans, 1966) and its radiant point for that date. This appears to be a rather circuitous method, but even if it involved a large error it would not affect his conclusion that the disappearance of the 5577A emission at low altitudes was due to some cause other than collisional deactivation.

4.6 SUMMARY

On the assumption that the intensity ratio I(3914A)/I(5577A) at any given altitude is proportional to the relative abundances of N_2 and OI at that altitude, an examination of the available data on atmospheric composition shows a strong dependence of the intensity ratio on the height of emission and hence on the energy of the incident exciting electrons. This leads to the conclusion that a hardening of the electron spectrum above about 25 keV (see below) will be reflected by a decrease in the ratio I(5577A)/I(3914A). In Chapter Seven some events are discussed which give experimental support to this conclusion. The ratio decrease seems to be due mainly to changing atmospheric composition, rather than to collisional deactivation, as has been previously assumed.

If it is true that atmospheric composition is more important than collisional deactivation in determining the I(3914A)/I(5577A) ratio, then experiments analyzed using the method of Omholt and Harang (1955) may give erroneous results. Evidence that this is so is provided by the results of Omholt (1955) which appear to contradict one of the basic assumptions of the analysis by which they were obtained. This indicates that an analysis of this type is not valid when neither the lifetime of the 5577A upper level nor the rate of excitation to this level (relative to that of the 3914A upper level) can be said to remain constant when the other varies.

A change in the electron energy spectrum below about 25 keV would not be expected to have much effect on the intensity ratio of the 5577A and 3914A emissions, since above 95 km (the penetration altitude of a 25 keV electron) the relative atomic oxygen and molecular nitrogen concentrations are roughly proportional, and collisional deactivation of the 5577A upper level is negligible above 95 km. On the other hand, changes in the spectrum above 25 keV might easily produce large changes in the ratio I(5577A)/I(3914A), and so this ratio may serve as an indication of the hardness of the electron energy spectrum, when measured in the auroral zenith.

The results of McEwan and Montalbetti (1958) can be interpreted as showing that of all the homogeneous and rayed arcs and bands whose height they measured at Churchill, only 7 or 8% had significant luminosity below 95 km. This gives a rough upper limit to the expected frequency of occurrence of changes in I(5577A)/I(3914A) for this type of aurora. While this upper limit may be valid only for solar maximum, when these height measurements were made (see also Section 5.3), Brandy and Hill (1964) reported that the height distribution of auroras seemed to agree with that found by McEwan and Montalbetti, within the experimental error.

To confirm the suggested relative importances of collisional deactivation and atmospheric composition, luminosity profiles of the 3914A and 5577A emissions, with a vertical resolution of 1 km or better, are desirable. Rocket measurements appear to be best suited to this work. Simultaneous measurements of the incident electron spectrum would also assist greatly in establishing the exact relation between the electron energy spectrum and the ratio I(5577A)/I(3914A).

CHAPTER FIVE

COLOUR VISION AND THE AURORA

The confluence of physics, physiology and psychology in the study of colour vision has by no means led to unanimity on the subject. Opinions still differ on the number of mechanisms involved in the perception of colour by a normal observer (Osgood, 1953; Land, 1959; Belsey, 1964), and on the nature of the basic process responsible for transforming an optical signal on the retina into an electrical signal in the optic nerve. However, for the purposes of this discussion the 'classical' Young-Helmholtz three-receptor theory of colour vision will be adopted. Other theories which have been proposed from time to time are essentially modifications of this theory.

5.1 COLOUR VISION THEORY

Before details of the classical theory are discussed, the conditions under which it may be applied should be made clear. Firstly, the following remarks apply directly only to additive colour mixing (mixing of beams of light) as opposed to subtractive colour mixing (mixing of pigments), where the word 'colour' is taken to mean the sensation produced by a given visual stimulus, i.e. colour is a subjective reaction. Secondly, the theory is strictly applicable only under bright light conditions in which the 'cones,' which are mainly responsible for colour perception, are the dominant receptors. Below a certain light level, which varies with wavelength, receptors known as 'rods' come into use, and these have almost no ability to distinguish colour, so vision in dim light is essentially achromatic.

The centre of the retina, the fovea, is composed almost exclusively of cones and hence this is the part of the eye normally used for high definition vision in bright light. Rods on the other hand dominate the periphery of the retina and so colour perception is poor for objects at the edge of the field of view and at the same time visual definition is reduced. Averted vision should be used to see faintly luminous objects at night. This is done by fixing the eye about 10 degrees to one side of the point of interest; in this case the increased sensitivity of the rods usually compensates to some extent for the loss of definition and colour perception caused by their use.

The three-receptor theory of colour vision is based on three experimental observations which suggest that the eye perceives colour through the action of three light-sensitive receptors, having their peak sensitivities in the blue, green and red regions of the colour spectrum.

In this context the word 'light,' meaning the source from which visible radiation emanates, as opposed to the radiation itself, refers specifically to an area or spot on a screen, formed by shining a coloured beam onto the screen. To "mix" two lights, two beams are directed onto the same area of the screen, and to "compare" two lights, the two spots are shown side by side and, normally, simultaneously. The words 'light' and 'mix' have the above meanings in the following statement of the three basic observations.

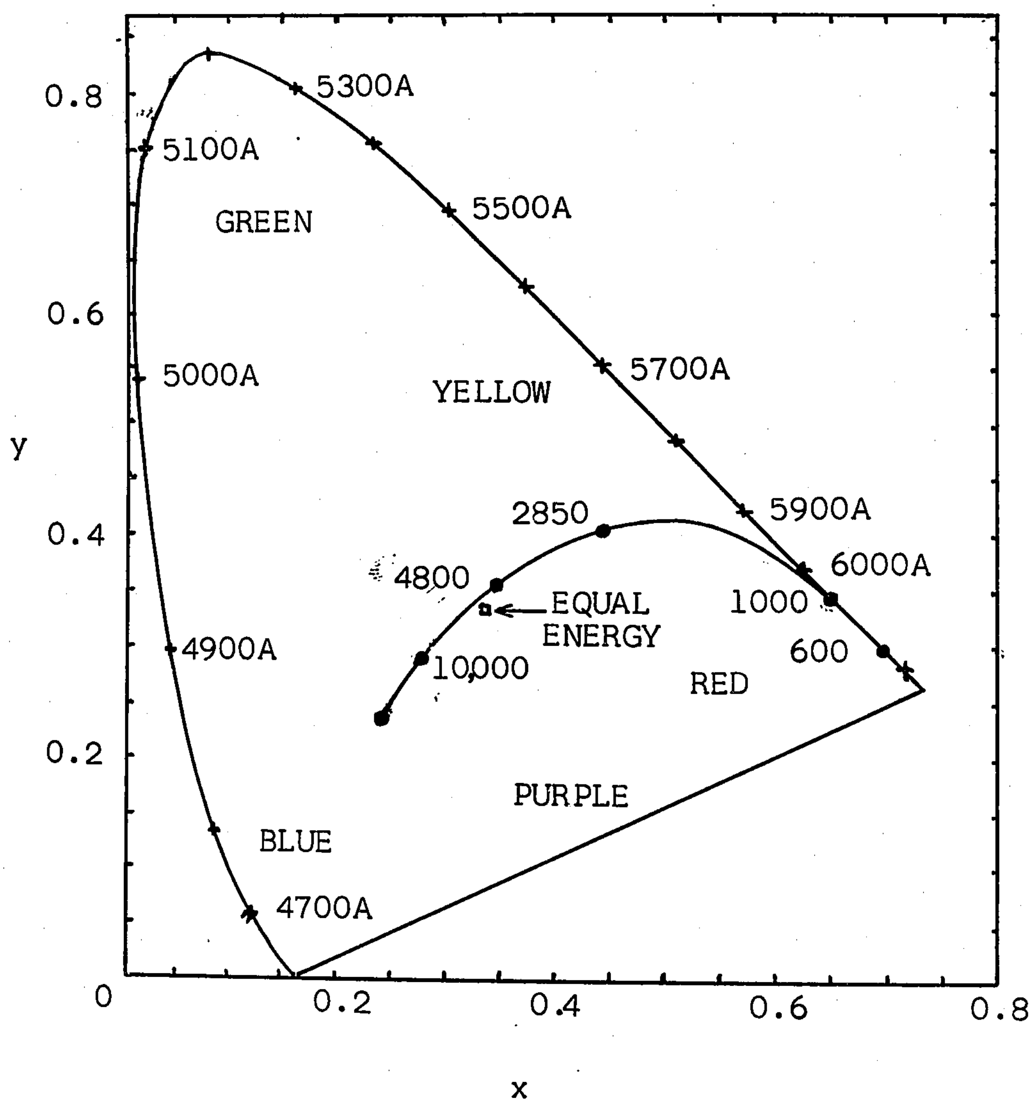
1) When two lights have different colours their spectral compositions must be different, but the converse is not true. Two lights can have the same colour but different spectral compositions, in which case they form a 'metameric' pair. For example, yellow light may be produced by mixing red and green light, thus giving one component of a metameric pair, whose other component is produced by a 5700A source. Two lights of exactly the same spectral composition always have the same colour: they are said to form a 'non-metameric' pair. All observers, whether colour-blind or not, should agree on a (simultaneous) match of a non-metameric pair (same composition, same colour); minor differences in the relative colour responses of 'normal' observers may lead to disagreement in matching light of different compositions so that what is a 'metameric' pair

(different composition, same colour) for one observer may not constitute a matched pair at all for another observer (different composition, different colour). It is therefore not surprising that people often differ on the name of the colour of an object: the difficulty goes somewhat beyond the usual problem of applying a linguistic label to a concept.

2) The second experimental observation is that two lights can always be matched by varying only three quantities: hue, saturation, and brightness. The hue tells us whether blue, red, green etc. is involved; the saturation denotes the amount of white light admixture, e.g. pale green, deep blue, pink, and so on; and the brightness depends on the intensity of the radiation received by the eye. The three quantities are not quite independent, and this fact is the explanation of the Bezold-Brücke phenomenon (Judd, 1951, p.854), in which the hues of most lights change with luminance (brightness) due to an after-image effect: e.g. a bright red spot tends to induce a greenish tinge in a white spot observed after it, or a whitish tinge in itself if observation is prolonged. It is also found that red, yellow, green or blue lights often exhibit a decreased saturation but little hue change with increased luminance, but yellowish red and yellowish green become yellower at high luminance, and bluish red and bluish green become bluer.

3) The third basic experimental observation shows that any two lights can be matched for hue and saturation by varying the relative proportions of three suitable 'primary' colours; despite the name 'primary' these colours are not unique. Thus it is possible to draw up a system using standard illuminants R (reddish), G (greenish), and B (bluish), which describes a light of any hue or saturation by the relative amounts of R, G and B required to synthesize it, i.e. to reconstruct on the screen beside the 'unknown' light a light of the same colour, according to an arbitrary 'standard observer,' which generally means an average of a large number of observers.

The standard illuminants chosen by the International Commission on Illumination (ICI, or, from the French, CIE) are 4358A, 5461A (two lines in the mercury spectrum) and 7000A. With these and any other actual sources, it is frequently found necessary to specify negative amounts of R or G or B, where a 'negative amount' in the synthesized spot signifies that a positive amount is to be added to the 'unknown' spot. To avoid this difficulty a transformation was applied to the RGB colour-space so that colours could be specified in terms of non-negative orthogonal quantities X, Y, and Z, where these define a new three-dimensional colour-space. Strictly speaking, X, Y, and Z define a 'chromaticity space,' where 'chromaticity' is an



The central curved line (the 'Planckian locus') represents the chromaticities of a black-body radiator (figures on this line are temperatures of the radiator in °Kelvin). (From Judd, 1951.)

FIGURE 2

THE ICI x-y CHROMATICITY DIAGRAM

objective quantity used in place of subjective 'colour,' but this distinction is rarely adhered to. Each point in XYZ space represents a definite fixed <u>chromaticity</u>, but the <u>colour</u> corresponding to this point may be different for different observers. Since the sum $(X + Y + Z)$ gives an indication of the brightness, which is not usually of great interest, two-dimensional representation is achieved by specifying only two of the three quantities, x, y, and z, where $x = X/(X + Y + Z)$, $y = Y/(X + Y + Z)$ etc.

Figure 2 shows the location of spectral colours on the x-y diagram. Points outside the closed area do not represent real colours. Such colours as brown and olive do not appear since they are not genuine colours: the sensation of brown, for example, occurs through the contrast of an orange light with other lights in the same field of view and of higher luminance, and olive-green arises in a similar way from yellow-green. Put in another way, there is no such thing as an illuminated brown object in an otherwise dark room.

5.2 COLOUR VISION AT LOW LIGHT LEVELS

5.2.1 Grassman's Laws

With the aid of the x-y chromaticity diagram and the x, y and z trichromatic coefficients (given in e.g. the Handbook of Chemistry and Physics, 1964) it is possible

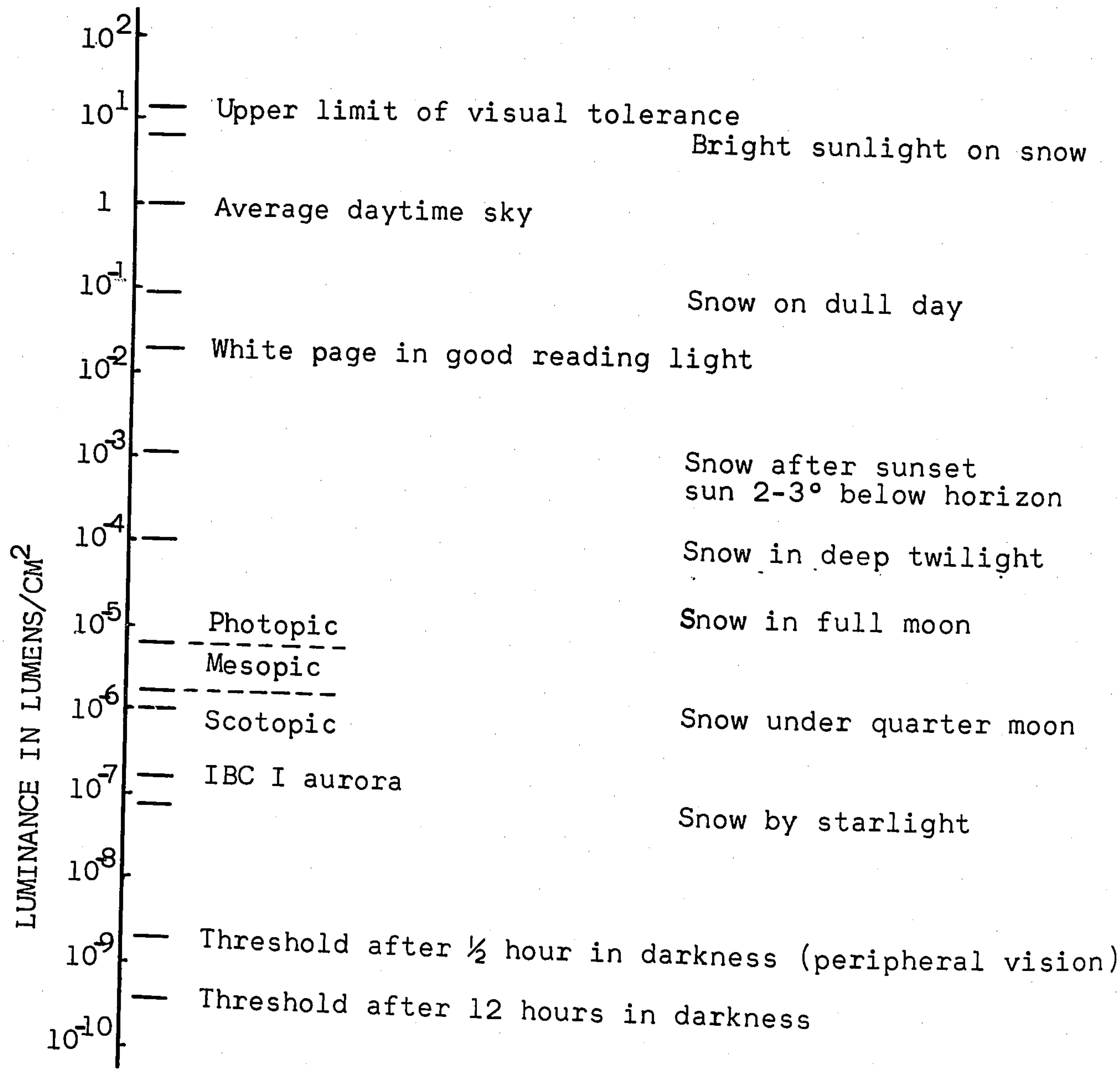


FIGURE 3

LUMINANCE RANGE OF HUMAN VISION

to calculate the final chromaticity produced by mixing any number of spectral emissions, and from this to estimate the colour. This is done by assuming that Grassman's Laws (Judd, 1951) hold true:

1) When equivalent lights are added to equivalent lights the sums are also equivalent.

2) When equivalent lights are subtracted from equivalent lights the differences are also equivalent.

3) Lights equivalent to the same light are equivalent to each other.

Unfortunately, in the luminance range in which aurora of IBC I and II fall, Grassman's first and second laws do not hold, because vision in this range is effected partly by cones and partly by rods, while Grassman's Laws hold only for cone vision. Figure 3 shows the relation of this transition region to the full range of perception of the eye, after Bartley (1951) and Judd (1951). The various levels in the diagram refer to spots of about 20° angular area. Good agreement should not necessarily be expected to occur between the levels in the diagram and those for a particular observer.

The sensitivity of the eye of course depends on the state of dark adaptation to dim light. In general, adaptation depends on the nature and intensity of the illumination previously encountered and consists of two distinct phases:

an initial phase covering approximately the first ten minutes in the new situation, when an increase in sensitivity of about a factor of ten occurs; and a secondary phase which may continue for several hours. During the first half-hour of the secondary phase the sensitivity of the eye may further increase by a factor of 100 (Bartley, 1951). The pupillary area varies over a total range of 7 to 1 and is a minor factor here. Initial dark adaptation seems to be due to the slow reactivation of rods, and the secondary phase arises from chemical changes in the rods leading to greatly increased sensitivity.

5.2.2 Scotopic, Mesopic and Photopic Vision

The region in Figure 3 between scotopic (rod) vision and photopic (cone) vision, termed the mesopic region, is one where distorted colour vision is possible. Full colour vision is possible only in the photopic region. It is extremely difficult to make accurate calculations on visibility in the mesopic region, mainly because the position of the region may vary widely from one person to another.

5.2.3 Wavelength Effects

The changeover from scotopic to photopic vision introduces the further complication that the visibility vs wavelength curves for the two processes are different in

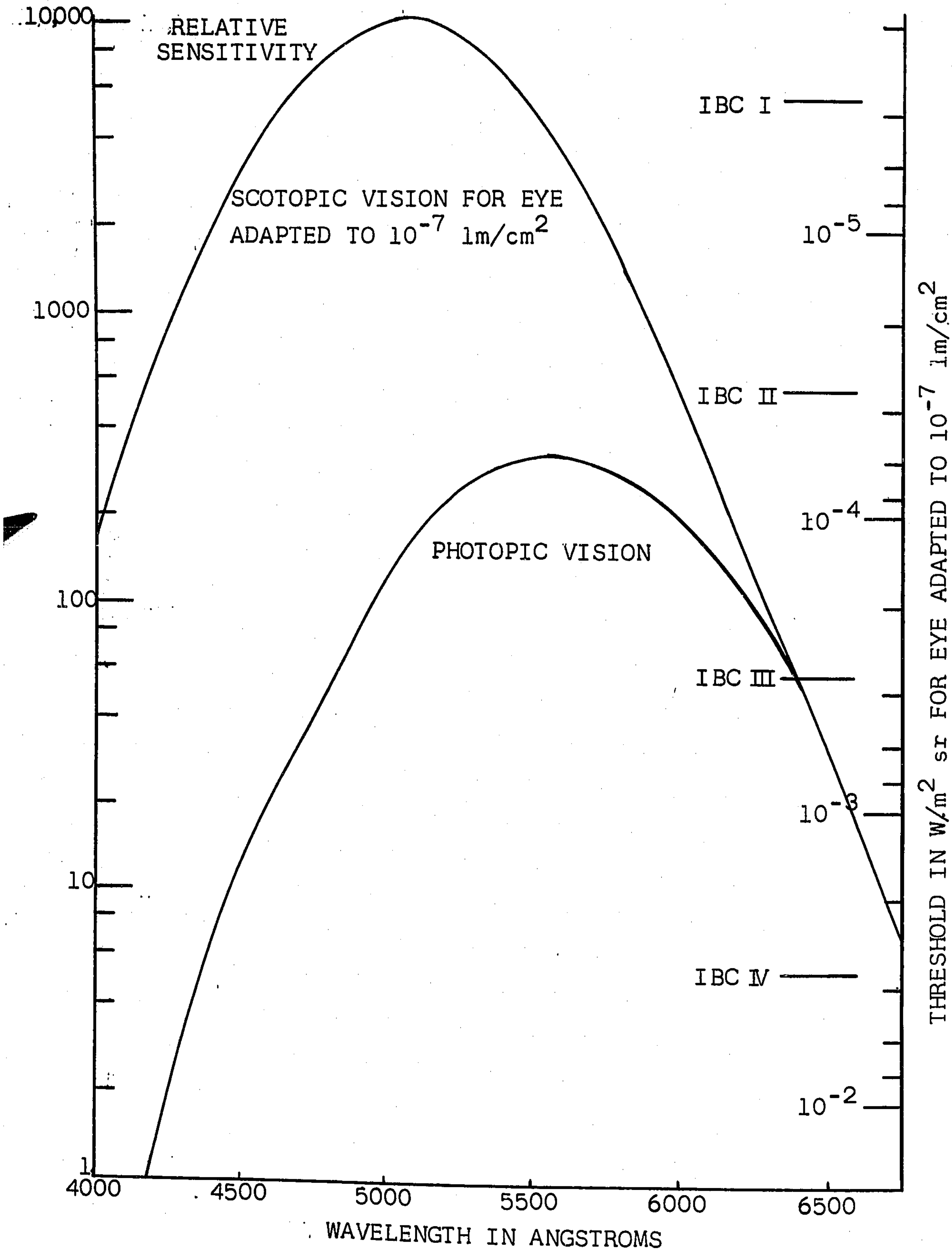


FIGURE 4

SCOTOPIC AND PHOTOPIC VISION
WAVELENGTH DEPENDENCE

shape as well as in absolute peak sensitivity (Figure 4). It may be noted here that the quantity Y has the same relation to wavelength as the photopic sensitivity, thus the latter is readily available from tables of Y as a function of wavelength (Bouma, 1948).

From Figure 4 several predictions can be made about low light level vision. First of all, at wavelengths greater than 6500A the thresholds for rod and cone vision coincide, and thus a red light always appears red as soon as the eye notices it. On the other hand, a blue light whose brightness is increasing from zero will be perceived by the rods as a colourless (white) light long before any blue sensation appears.

Consider three lights A, B, and C, consisting of spectral lines 4700A, 5500A and 6500A respectively, whose radiant intensities (i.e. radiated power) are equal and can be varied in step from total darkness to very bright conditions. For a normal eye light B will be the first to show up as the intensity is increased above the absolute threshold of the eye, but no colour will be observed at this stage. An intensity increase of a factor of 1.5 enables A to be seen as a colourless light also, and a further increase of a factor of 20 shows up B as green, while C will still be invisible. To make C visible a further increase of a factor of 10 is required, but at this time C should be visible as red without going through any intermediate colourless stage. At this time also A should begin to show up as blue, after being perceived long before as a 'white' colour.

It is evident from the above that low brightness conditions tend to decrease the visibility of red as compared to green; this is the Purkinje effect, discovered in the last century through the observation of red tulips on a lawn at twilight (Bouma, 1948). The Purkinje effect is relevant to auroral observation since the wavelengths of the $[OI]_{32}$ line and the visible N_2 1PG emissions approximate those of lights B and C above.

Source A simulates the (0,2) band of the N_2^+ 1NG system at 4709A. Although this band has intensity only 6% of that of the 3914A (0,0) band (Petrie and Small, 1953), it still has a greater effect on the eye since the visibility functions are in the ratio 100:1 approximately. The (0,1) band at 4278A (30% of (0,0) band intensity) is also more intense than the (0,2) band but its smaller visibility function reduces its visual importance to about the same value. The product Relative Scotopic Visibility x Intensity for the (0,0), (0,1) and (0,2) bands respectively are as 1:4.7:5.4. These figures do not change greatly whether scotopic or photopic vision is being considered but for most auroras (up to IBC III+

scotopic vision will be the mechanism in use, and hence it seems likely that these bands may contribute greatly to auroral colourless glows, but only rarely give a blue colour either by themselves or as part of a display involving other emissions.

5.3 DEDUCTIONS FROM COLOURS IN AURORA

The ICI chromaticity diagram provides information on the possible altitude separation of green and red emissions, i.e. on the height dependence of the corresponding intensity ratio. If an IBC III Class c aurora is assumed to have an N_2 1PG total intensity of about 500 kR (Broadfoot and Hunten, 1964) the final colour effect for the standard observer can be calculated (Appendix). If Chamberlain's value of 2000 kR is used instead (Chamberlain, 1961, p.197) some of the numerical results change but the main conclusions remain unaffected. The observational results of Chapter Seven indicate that 500 kR is more nearly the correct figure to use.

Even if nothing is known about the relative intensities of auroral emissions other than that the 5577A line is the strongest visual feature in the aurora, it is clear that coincident luminosity profiles for all emissions could lead only to a homogeneous yellowish green or white aurora, but not to a green layer with a red lower border, as is in fact observed. Therefore the calculation suggests that a separation of the red and green emission profiles does exist, and that an IBC II Class c display can develop into a Class b display in three ways:

1) The incident electron energy spectrum steepens so that the height-integrated value of the N_2 1PG/5577A intensity ratio increases to about ten times its height-integrated value in a 'normal' Class c aurora. This occurs if the electron spectrum hardens considerably, with perhaps little change in the total electron flux. The green upper layer would probably look only slightly brighter than the red lower border in this case.

2) Alternatively, the electron spectrum could remain unchanged but the total electron flux could increase by a factor of ten or more, thus causing the lower-altitude red emissions, which had been below the colour vision threshold, to rise above it, and hence become visible as the red lower border. In this case, one would expect that the green regions at higher altitudes would seem much brighter than the red lower border. For the lower border to redden in this way, the initial incident electron spectrum would have to include significant numbers of electrons of energies up to about 100 keV. Thus the monoenergetic (approximately 6 keV) auroral electron flux reported by McIlwain (1960) could not cause a Class b aurora, since the particles

could not penetrate far enough into the atmosphere (see below).

3) Processes (1) and (2) could occur simultaneously.

The basic assumption here is that the 5577A and N_2 1PG luminosity-height profiles do not coincide, and that the 5577A profile is the higher of the two. Some evidence for this separation has been discussed in Chapter Two, but the most obvious proof is that Class b displays do occur, showing that the red emissions, in spite of their lesser visibility coefficients, become visually dominant in the lower border.

Regardless of the height-integrated spectral composition of the aurora, a red colour will appear when the N_2 1PG total system intensity is enough (about 500 kR, or about the same as in an average IBC III aurora) to bring some of its constituent bands over the colour threshold of the eye, provided only that the green profile is sufficiently separated from the red profile that the two colours appear separately rather than as a mixture.

The red appearance of a Class b lower border indicates that in this altitude region the red emissions are at least ten times visually stronger than the green emission, otherwise only green or yellow would be perceived. From the calculation in the Appendix, it appears that a source which consists solely of the N_2 1PG system, with a total intensity of 2000 kR, is visually equivalent to a single emission line at about 5950A, with an intensity of about 90 kR. This N_2 1PG 'equivalent source' would have a visual brightness 15% of that of a 5577A source of intensity 400 kR. Thus an auroral display with this composition [I(5577A) = 400 kR and I(N_2 1PG) = 2000 kR] has an average ratio I(N_2 1PG)/I(5577A) which is at least 60 times smaller than that existing in the lower border of a Class b display.

Comparing this result with the atomic oxygen and molecular nitrogen concentrations given in Table 1, we find that the relative abundance of atomic oxygen, relative to that of molecular nitrogen, at a height of about 84 km is only one-sixtieth of its value at 115 km and above. If it is assumed that the N_2 1PG intensity/height profile is roughly similar to the concentration/height profile of N_2, and that the height-averaged value of the ratio I(N_2 1PG)/I(5577A) in a display is of the same order as the actual ratio at an altitude of about 115 km, then it might be expected that the red lower border of a Class b display would occur only at altitudes of about 84 km and lower. If the value of I(N_2 1PG) in an IBC III aurora is taken to be 2000 kR instead of 400 kR (Chamberlain, 1961, p.197), the expected upper altitude of the red region will be about 88 km rather than 84 km.

It must be emphasized that these calculations are not very precise, but even if the intensity ratios used are wrong by an order of magnitude the calculated height varies by only about 5 km. The height obtained is in agreement with accepted values of the heights of Class b lower borders, indicating that atmospheric composition may play a large part in causing Class b red lower borders.

Colour vision theory leads one to expect a yellow region where the red and green regions meet (cf. Chamberlain, 1961, p.125). This yellow region is very difficult to observe even when one is looking for it specifically, and its virtual absence indicates that the green/red transition must be very sharp indeed. The apparent lack of reported observations suggests that the yellow transition region must be very thin, probably less than 2-4 km. Since the ionization caused by monoenergetic electrons falls off much more rapidly with decreasing altitude than with increasing altitude (referred to the altitude of maximum ionization), it seems probable that the sharpness is due to a rapid fall-off at the lower edge of the green region rather than to a rapid fall-off at the upper edge of the red region. If so, this would support the findings of Chapter 2 that the disappearance of the green emission is caused by lack of atomic oxygen rather than by the much more gradual deactivation process.

Although no systematic data are available, there seems to be some evidence for an anti-correlation of the frequency of occurrence of Class b auroras with the solar cycle (D.J. McEwan, private communication, 1965; Bates, 1960). Since there is some weak support for a lowering of the atmospheric atomic oxygen layer during periods of increased solar activity (Halliday, 1960), it might be conjectured that at solar maximum the atomic oxygen layer lies low enough in the atmosphere that the green emission is able to mask the red emissions of N_2 1PG, giving a yellow or yellow-green mixture rather than a distinctly red lower border. The experimental basis of this proposal is extremely weak, but it could probably be checked fairly readily by searching for a lowering in the height of the green emission at solar maximum.

It should be noted that an estimate of the visual green/red ratio is useless, if neither the spectrum of the incident electrons nor the brightness of the aurora is known. For example, in Case (1) discussed above, the visual brightness ratio between the green upper and red lower regions can vary from infinity (only green visible) to about 10 (when the aurora gets bright enough so that many red emissions are well above the colour threshold). Thus this visual change, by itself, does not imply anything about the photon emission ratio, which in Case (1) remained constant.

It thus seems possible that there may be no essential difference other than brightness between certain Class c auroras and certain Class b auroras. This will be more likely for displays of Class c aurora at times when the electron energy spectrum is fairly hard, as at these times a small flux increase may be all that is necessary to cause the appearance of red at the lower edges of the display.

The observations of Sandford (1961) in Antarctica are interesting in view of what has been said above. By using high-speed colour film in an all-sky camera he found that red aurora ('Type A red,' probably Class d) occurred much more frequently than simultaneous visual reports indicated, and from this he concluded that this type of aurora, far from being very rare, as is often assumed, may even have been the most common during the period under study. Laboratory tests on the film used, and comparison with visual reports, indicated that the colours recorded were real and not due to inadequacies in the film or the processing. This view was supported by comparison of spectrograms and colour films for suitable auroral forms such as isolated quiet arcs.

A similar observation was reported by Davis (1965), who used an image orthicon television camera, coloured filters, and colour film for cinemaphotography of auroras at Churchill. Considerably more red and blue was revealed than visual observation indicated, but the colour response of the camera and filters was probably not as closely matched to the human eye as that of the colour film, and there was probably some colour distortion.

CHAPTER SIX

EXPERIMENTAL APPARATUS

6.1 PHOTOMETER CHARACTERISTICS

A balloon-borne X-ray detector of the type flown by the UAC group has a rather loosely-defined cone of acceptance of the order of 60° half-angle. Luminosity measurements intended to be compared with the X-ray data should be made using a photometer with a wide field of view, covering the same region of the sky as the X-ray detector. It was decided that two photometer channels were desirable, each monitoring a different auroral emission. On all photometers which were constructed, the 3914A band was monitored to give an estimate of the total energy flux into the atmosphere while the second channel measured either the intensity of the 5577A OI line or the intensity of the N_2 1PG system.

Problems arising from the scattering of extraneous light into the photometers by the 50-foot diameter balloon can be partially overcome either by using a system of baffles to block out the balloon or by suspending the instrument package from a long (up to 500 feet) line which is wound out automatically after the launching of the balloon, or both,(as was done by Rosenberg, 1965). In

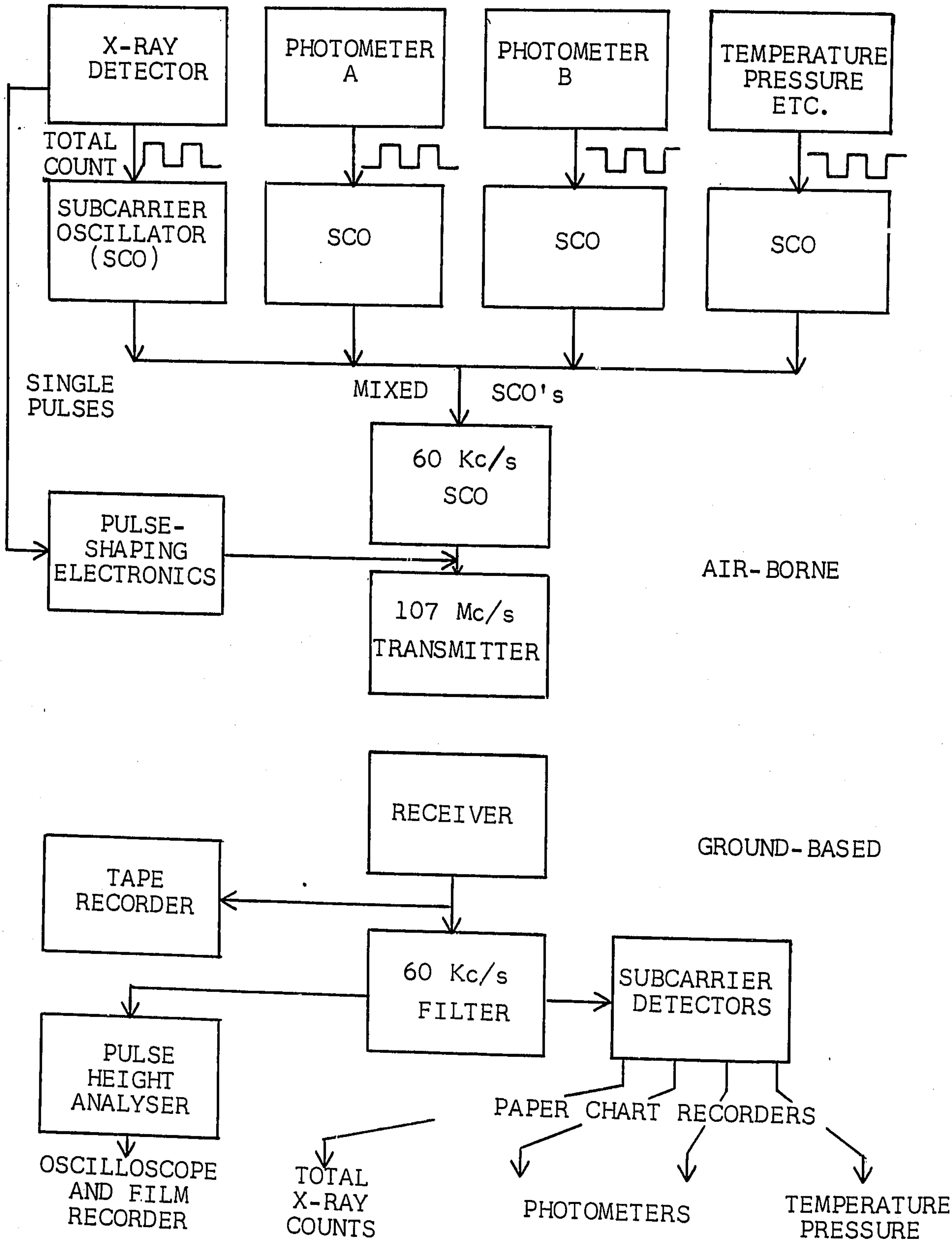


FIGURE 5

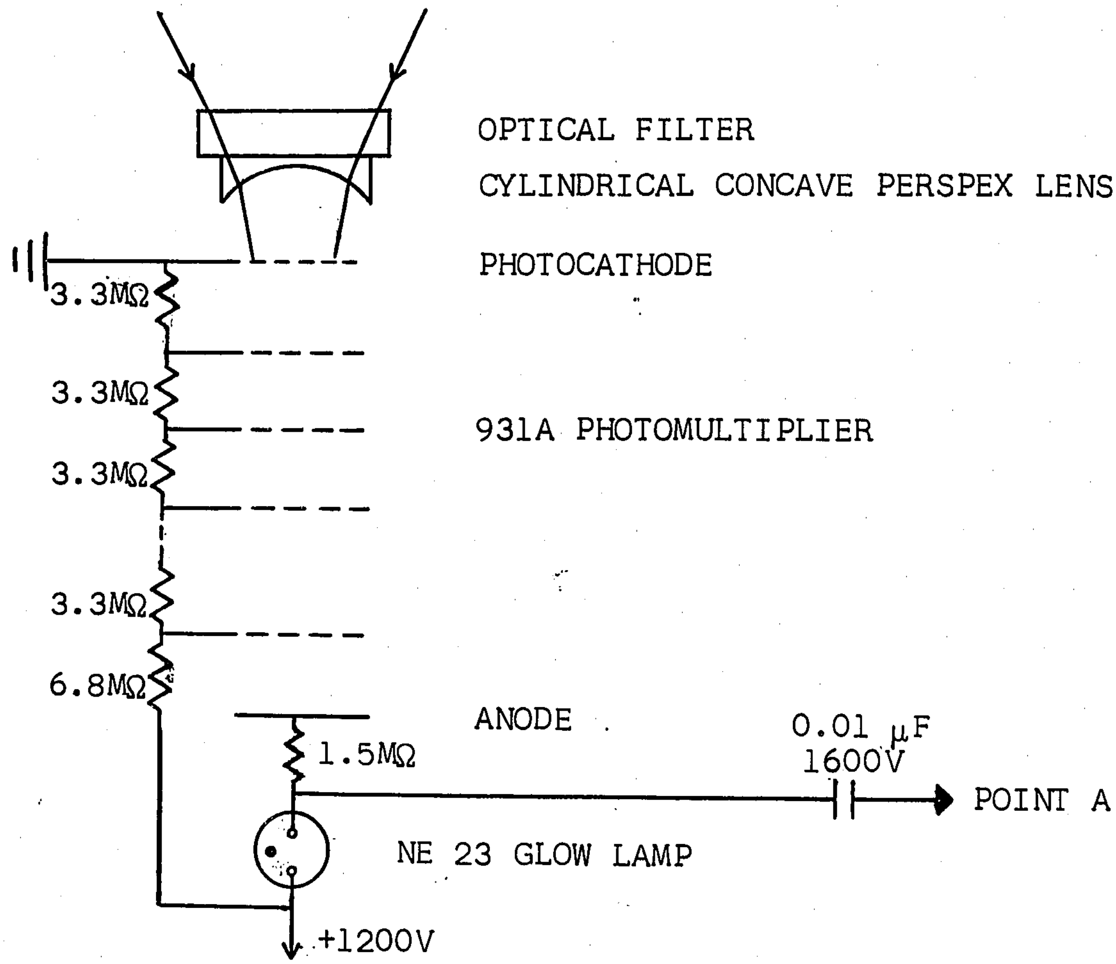
TELEMETRY CHAIN FOR BALLOON EXPERIMENT

the flights to be reported here the line-suspension system was used; however in two cases the wind-down mechanism gave trouble by unwinding too rapidly and allowing the package to hit the ground immediately after launch.

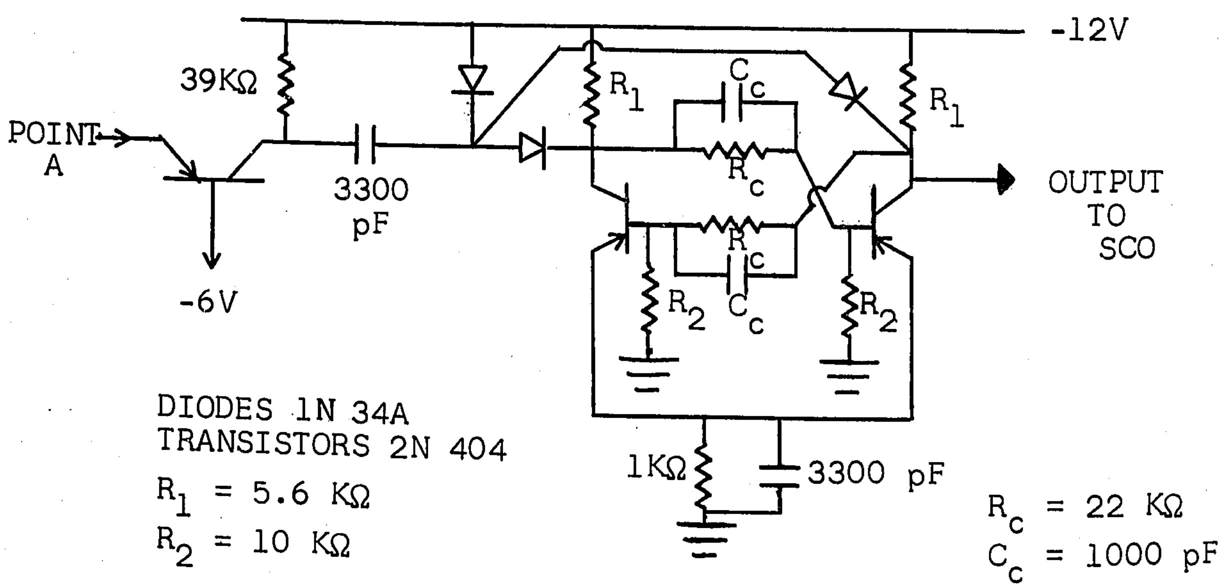
A further requirement for the photometers was that they should be of simple design so as to have a light weight with low power consumption, and that the output signal to the transmitter should be clear and unambiguous, preferrably in digital form. The telemetry chain is shown schematically in Figure 5 . The signal from the photometers is a square wave whose frequency depends linearly on the auroral light intensity. An amplitude-modulated sub-carrier is gated on and off by this square wave, and the mixed output of several such carriers is used to frequency-modulate the 107 Mc/s transmitter. Besides photometer information, the subcarriers also carry pressure, temperature, and other 'housekeeping' data. On the ground the receiver is analysed in real time, i.e. the information from the subcarriers is decoded and recorded on paper charts. The receiver signal is also tape-recorded to ensure continuous acquisition and to facilitate later data analysis.

6.2 PHOTOMETER ELECTRONICS

The physical configuration and electronics of the photometers are shown in Figure 6 . The photomultipliers



Circuit elements to point A are potted to prevent high-voltage corona.



<u>FIGURE 6</u>

PHOTOMETER ELECTRONICS

used were GE 931A nine-stage side-window types, operated at 120 volts per stage. The required voltage per stage was supplied from a resistor bleeder chain across a 1200 volt d.c. supply. This high voltage supply at a current of 60 to 100 microamperes was provided from a circuit consisting of a 6 volt oscillator and step-up transformer acting through a rectifying and voltage-trebling diode network. The same power supply was used for the X-ray scintillator detector. The high voltage was regulated to within 0.5% throughout the flight (until battery run-down) by a corona voltage regulator circuit applying feed-back to the low voltage oscillator.

The signal current to be measured is of the order of 10^{-6} to 10^{-8} amperes. This current is converted to digital form by a relaxation oscillator consisting of a neon glow lamp and a high voltage capacitor (Figure 6). The signal current from the photomultiplier anode discharges the capacitor until the voltage across the neon lamp is sufficient to fire the lamp. The capacitor then charges rapidly through the lamp until the voltage across the lamp falls below the maintaining voltage and the neon discharge is extinguished. Following this the signal current again begins to discharge the capacitor and the cycle repeats. At each successive neon discharge a positive pulse appears at the input to the first transistor. The output signal from this transistor

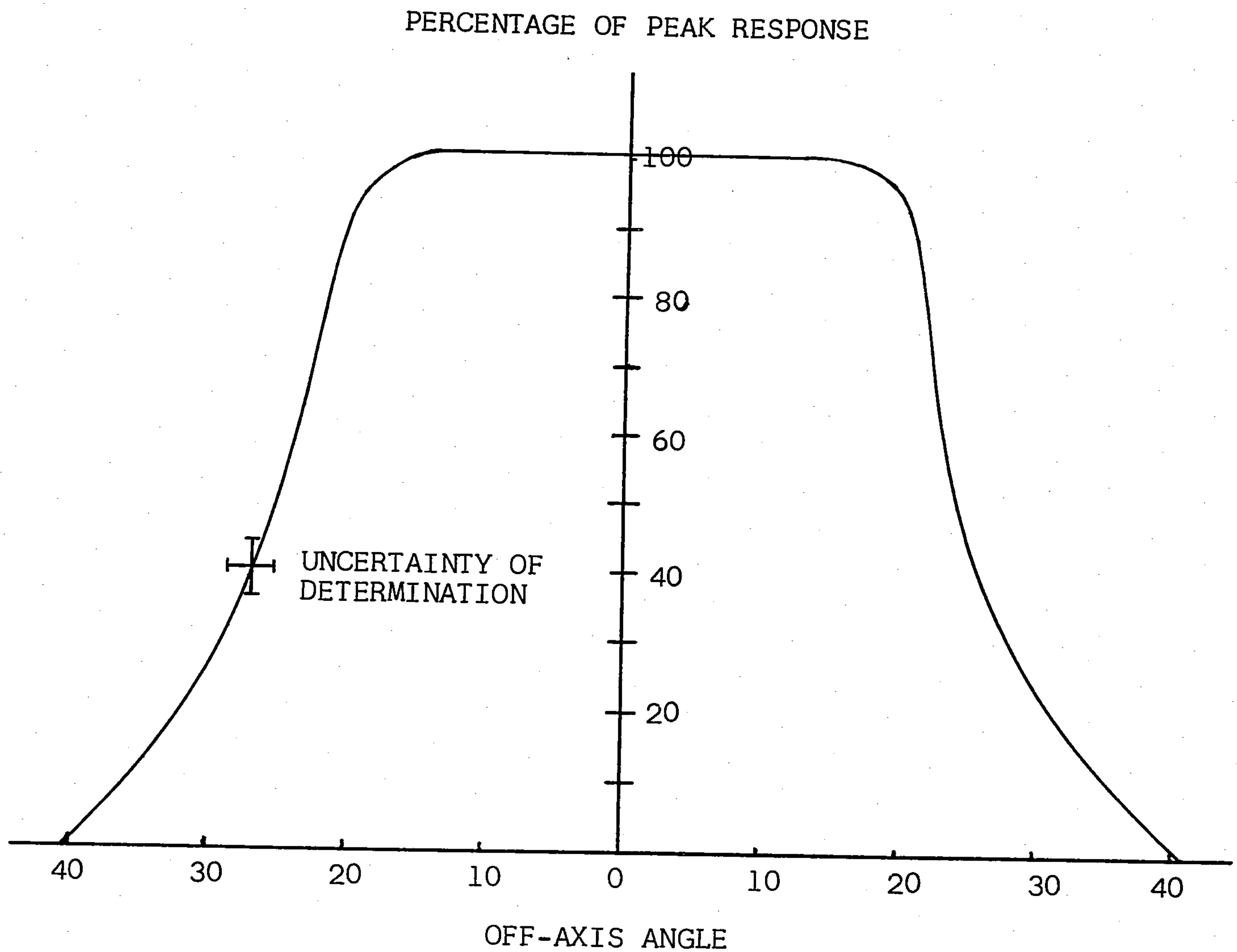


FIGURE 7
PHOTOMETER ANGULAR RESPONSE

is differentiated and used to trigger the flip-flop, which provides a square wave signal for the subcarrier input.

The photomultiplier tubes used were selected for low dark current. This was especially necessary for tubes used for detection of the red N_2 1PG emissions, as the signal to noise ratio is decreased drastically in this spectral region. This follows from the reduced red sensitivity of the S-11 cathode relative to blue or green. The neon lamps and the high voltage capacitors were also selected for low leakage current, since it was found that some of these components (especially the capacitor) had leakage currents comparable to the expected signal.

6.3 PHOTOMETER OPTICS

Wide angles of view were obtained by using close-fitting cylindrical concave perspex lenses between the windows of the tubes and the glass filters. The full width at half-maximum of the angular response of the photometers used in this work was 50° ± 3°; the response was essentially flat for 20° on either side of centre (Figure 7). The cross-section of the solid-angle field of view was not circular, but resembled a square with rounded corners. The angular response curve given applies to two mutually perpendicular axes in line with the sides of the square. The orientation of the axes of the field of view with respect to the ASC pictures is not known precisely.

The difference in the fields of view of the photometers used is estimated to have an upper limit of 10%. If the aurora were always diffuse and widespread, a difference in fields of view would be of little consequence, but for the special case of dark sky directly in the field of view of the photometers and a single bright form near the edge of the field of view a large error in the intensity ratio might conceivably result. These circumstances would almost certainly cause large errors in the intensity ratio measurement because of scattered light, even if the fields of view were perfectly coincident, and therefore examination of the ASC pictures has been used to detect such circumstances, in the events reported in Chapter Seven.

A layer of electrically conducting paint, at cathode potential, on the glass envelope (other than the window) provided electrostatic shielding and also some degree of light shielding for the photomultiplier tube. Further light shielding was obtained through the use of black perspex boxes which surrounded the tubes and also served as filter holders. The black perspex was not completely opaque, and the interiors of the boxes were therefore coated with several layers of flat black paint.

To obtain the desired spectral response for each

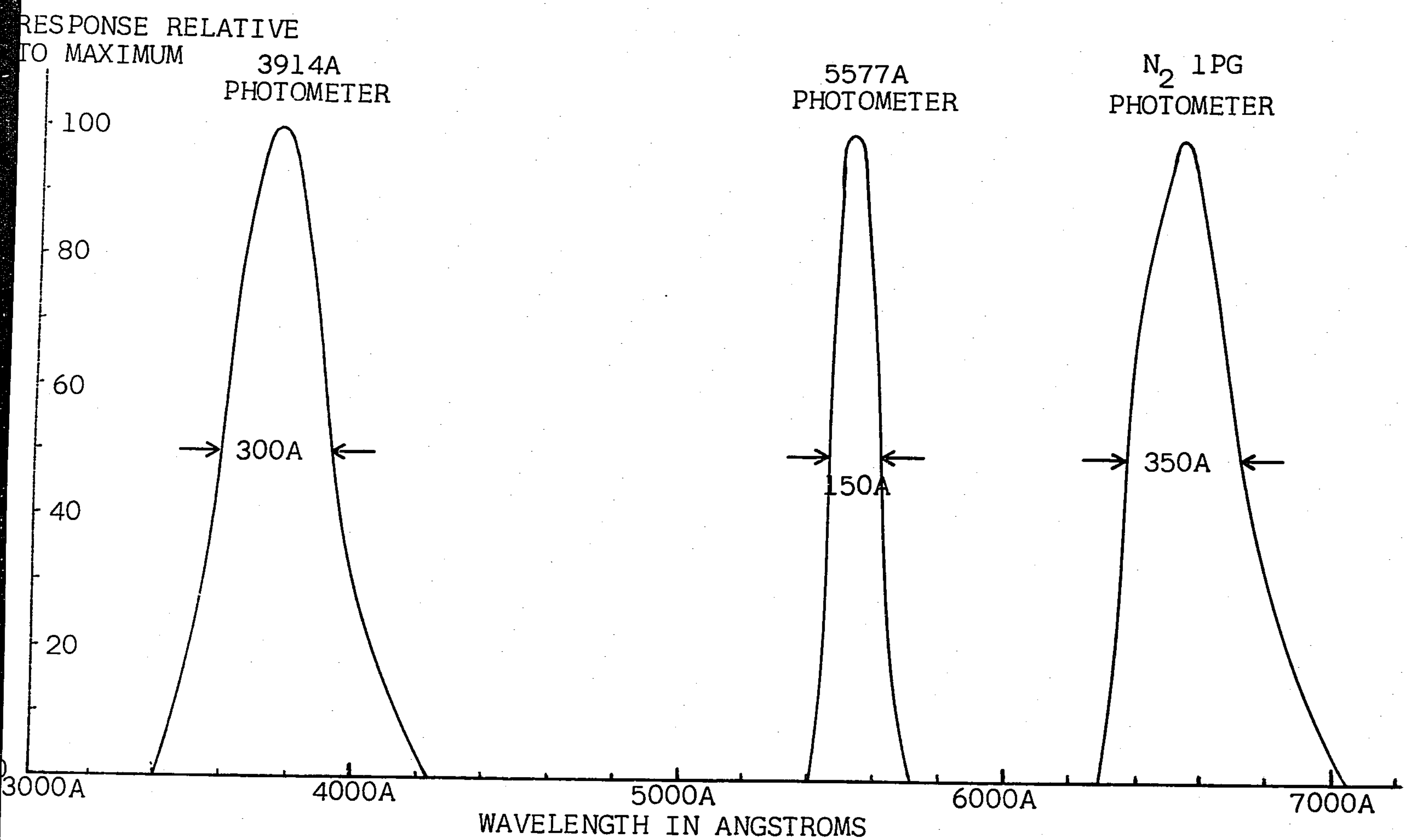


FIGURE 8

PHOTOMETER SPECTRAL RESPONSE

photometer channel, glass filters of wide passband were employed. Interference filters would not have provided significantly better selectivity of the various wavelengths since to use these filters to the best advantage the incident light must impinge normally on their surface: this requirement could not be reconciled with the desired wide angle of view without using collimating optics which would have increased the complexity of the system considerably.

The spectral response of the S-11 photomultiplier cathode when combined with the transmittance of selected Corning glass and Wratten filters (Corning 7-51 and 0-51 for 3914A, Corning 2-58 for N_2 1PG, and for 5577A a sandwich of Corning 3-68, Corning 4-96 and Wratten 77A) was found to give satisfactory rejection of a background continuum of up to 5 Rayleighs per Angstrom. The final spectral response of each photometer, normalized to unity at the wavelength of maximum sensitivity, is shown in Figure 8.

6.4 CALIBRATION OF PHOTOMETERS AND ANALYSIS OF RECORDS

Calibration of the photometers was carried out using a secondary standard low brightness source whose output had been previously calibrated in kiloRayleighs per Angstrom for the relevant spectral region at the Institute of Upper

Atmospheric Physics, University of Saskatchewan. From a knowledge of the spectral response of the filters (determined experimentally using a recording spectrophotometer) and of the photocathode of the tube (from manufacturer's data), the frequency of the square wave output for a given simulated auroral intensity, covering the whole field of view, was calculated. The type of low brightness source used has been criticized by Broadfoot and Hunten (1964) because of its low blue and ultraviolet emission, which makes it somewhat unsuitable for absolute calibrations at wavelengths below 4000A. Hence as an absolute calibration this determination is probably not more accurate than ±20% at 5577A or ±60% at 3914A. However, changes in relative intensities can be compared much more accurately, to within about 5%.

The observed auroral intensities were calculated by finding the average pulse rate over 5 or 10 seconds and then using the calibration curve of the photometer to obtain the corresponding light intensity in kiloRayleighs. Intensity ratios were then calculated from the computed intensities of the different emissions.

For the period during which photometer observations were made with this apparatus at Churchill, the ratio I(3914A)/I(5577A) typically had a value of about 2.0, and the ratio I(5577A)/I(Total N_2 1PG) was about 0.5 on the one occasion (Event C, Chapter Seven) on which the reliable estimate could be obtained. (The method used to obtain I(Total N_2 1PG) is discussed later.) The value of the ratio I(3914A)/I(5577A) seems rather larger than has been reported by other workers, and never decreased below 1.9 when aurora was visible. Chamberlain (1961, p.197) indicates a value of about 1 for this ratio, and Dalgarno et al (1965) assume a value of 0.5. The large value obtained for this ratio might possible arise through the inadequacy of the low brightness source used for calibration, as mentioned above. The I(5577A/I(Total N_2 1PG) ratio seems to be a factor of about 2 larger than that suggested by Broadfoot and Hunten (1964), but the low brightness source should be more reliable in this spectral region. Another possible source of error might be that the spectral response of the photocathode in the red region is much different from the manufacturer's figures; if this is not so, the ratio given is presumably valid.

The photometers measuring the N_2 1PG and the N_2^+ 1NG intensities provide direct information only on the intensities of those bands that fall within their acceptance passband. However, the total intensity of a complete band system can be calculated from a knowledge of the photometer response and laboratory measurements of the relative intensities of the different bands in the system. This is done quite often, e.g. by Evans (1963), but for the N_2 1PG system in particular a large amount of error may be involved, possibly due to differences in temperature under laboratory and auroral circumstances.

Thus Broadfoot and Hunten (1964) concluded that the total intensity of the 1PG system has generally been over-estimated by a factor of 5 or 10, and that the value quoted by Chamberlain (1961, p.197) is in fact applicable to an IBC IV aurora rather than the IBC III to which he assigns it. Chamberlain's value is based in part on the work of Harrison and Vallance Jones (1957), who in their calculations assumed that $N_0/N_3 = 29$ by extrapolation from measured values of N_3, N_4, etc., where N_n is the population of molecules in the n^{th} vibrational level of the 1PG upper state. Broadfoot on the other hand measured this ratio and found a value of about 0.9 rather than 29.

The photometers described here were designed on the basis of Chamberlain's values of the intensities, and the response to the 1PG emissions was observed to be about a factor of 10 less than expected. This meant that neither the accuracy of measurement nor the time resolution on this channel was comparable to the others and the signal was little above the dark current level except during the one bright display (Event C) discussed above.

Tests of the photometers, using constant light sources, showed that the standard deviation of a single flash period corresponded to an uncertainty of about 0.08 kR at all light levels. The error in scaling the charts and converting the reading to intensity led to an error of about 2% of the intensity. Since the intensity ratio I(3914A)/I(5577A) was found to be about 2, the actual uncertainty in the ratio was about ±0.1 when I(3914A) was 10 kR or more, but increased rapidly with decreasing I(3914A), being ±0.2 and ±0.3 when I(3914A) was 5 kR and 2.5 kR respectively. The uncertainty marking on the diagrams, showing I(3914A)/I(5577A) for the events discussed in Chapter Seven, is ±0.1 and thus applies only to times when I(3914A) was 10 kR or greater.

6.5 GROUND-LEVEL OPERATION

For ground-level operation of the photometers the X-ray detector was removed and the six volt supply provided by a long cable running from the indoor equipment position to the outdoor location of the photometers. Other conductors in this cable carried the square wave signals from the flip-flops to be recorded on a multi-channel paper chart recorder. In ground operation four photometer channels were used to monitor white light, 3914A, 5577A and the N_2 1PG system. The white light provided an indication of the presence of moonlight, twilight and other non-auroral light increases. The presence of cloud cover was also recorded by this channel because of the periodic reflection by the clouds of the light from a rotating beacon at an airport six miles away.

Also for ground operation a Clairex CL 505 cadmium sulphide photocell was used as a bias resistor in the regulatory feedback loop of the power supply. This was used to cut off the high voltage supply to the dynode chain at dawn or in the presence of any other bright light, thus protecting the photomultiplier tubes against the effects of high dynode currents. The resulting decrease in the input current to the power supply opened a relay and switched off the paper chart recorder motor. Since this process was reversible, automatic operation was possible when an unambiguous timing system was available, e.g. IRIG Format B, but because the range of auroral intensities encountered was about 100 to 1, where brighter auroras required correspondingly higher paper chart speeds, manual control of the chart speed was necessary to ensure a reasonable paper economy combined with a legible record of the data.

To obtain the auroral intensities outside the atmosphere, from ground observations, scattering and extinction corrections should be made or, alternatively, relative intensities may be used if the zenith angle of the photometers does not change. This latter course is commonly employed in order to avoid the uncertainties in scattering corrections, thus results are frequently quoted in terms of relative intensities, e.g. Evans and Vallance Jones (1965), Ansari (1964). This is justifiable since accurate knowledge of the absolute intensity is seldom necessary. However, this procedure requires that the atmospheric scattering effect be almost constant across the field of view, so that it strictly applies only to narrow-angle photometers or to wide-angle photometers pointed at the zenith, otherwise motions of the form within the field can cause spurious intensity changes.

Zenith observations are feasible at Churchill since auroral displays frequently occur overhead. Intensity ratios under these circumstances differ from the true ratio by a fixed factor depending on the relative extinction effects for the emissions concerned. Scattering is negligible for isolated forms in the field of view but this has to be confirmed for each individual case from ASC pictures.

Because of the use of glass filters of different thickness for different emissions and the possible large angles of incidence of the light being measured, there will be a small apparent ratio change if a discrete auroral form moves across the field of view. This is caused by the exponential dependence of the filter transmission on thickness. A simple calculation shows that this ratio change is negligible, being only 2 or 3%. The actual ratio changes of up to 100%, or more usually 50%, are obviously unlikely to be due to such effects of position.

The dark sky intensities obtained during ground observations were about 0.6 kR at 3914A and 0.2 kR at 5577A, or at least 5 times the photomultiplier dark current equivalent intensity. The dark sky readings were not subtracted from I(3914A) and I(5577A) before computing the intensity ratio, since at least part of the dark sky intensity may have been due to electron precipitation, and hence would have been a relevant quantity; in any case the uncertainty would be much smaller than that arising from photometer variation and scaling of the records, discussed above.

The uncertainties listed do not include those due to scattering effects, which were variable and had to be estimated for each particular time, using all-sky camera pictures; nor do they include those due to field of view uncertainties, which have been discussed earlier.

6.6 SYSTEM APPRAISAL

Since the photometer system described above was designed for airborne operation while the results presented in this thesis were obtained on the ground it is of interest to examine the suitability of the system for its final operation as compared to its intended one.

The main comments centre on the manner of transmitting and recording the signal. A digital format was chosen initially as being more convenient for radio transmission than an analogue format using frequency-modulated subcarriers and automatic calibration signals, since gating of a subcarrier can be detected even when the received signal is barely above the background noise level. Ambiguity of signal level is also generally easier to avoid in a digital system than in an analogue one, and a much wider signal range can be accommodated before resorting to the use of logarithmic converters. However for ground-level operation the analysis of digital data in the form described proved to be extremely tedious. The peak pulsing rate of the photometers was about 100 pulses per second; this meant that the paper chart speed had to be 125 mm/sec or more. It was hoped to use an automatic data analyser similar to a frequency meter to perform a digital to analogue conversion but this apparatus was not completed in time and analysis of the data had to be performed manually.

Since some of the interesting features of the intensities varied on a time scale of about 30 seconds, 10 second sampling of the data was necessary. Much greater time resolution was possible (to 0.1 seconds for 5577A and 3914A during bright displays) but none of the supporting apparatus regularly available had a matching resolution and trial samples of high time resolution showed no interesting intensity variations. This absence of intensity variation may be due to the wide acceptance angle of the photometer allowing local luminosity variations (if they exist) to be swamped by the integrated intensity of the whole field of view. If an analogue system had been used for transmitting the signal the ratio measurements could have been made directly and continuously, thus saving much time.

The operating range of the photometers was adequate except for the previously discussed lack of sensitivity of the N_2 1PG photometer. The 6-channel Brush paper chart recorder provided a sufficient range of chart speeds at all times.

Other problems encountered were due to the operating situation of the photometers rather than the deficiencies of the system itself. During bright displays the intermittent use of other apparatus caused voltage fluctuations and occasional power failures. Voltage fluctuations were not great enough to affect the chart recorder or the photometer high voltage supply. During complete power failures (which rarely lasted more than 1 minute) no data were obtained. Interference from an instrumentation tape recorder caused a certain amount of riometer absorption data to be lost, again generally during times of auroral activity. On the other hand, because of the isolated location extraneous light rarely interfered with the photometer measurements.

CHAPTER SEVEN

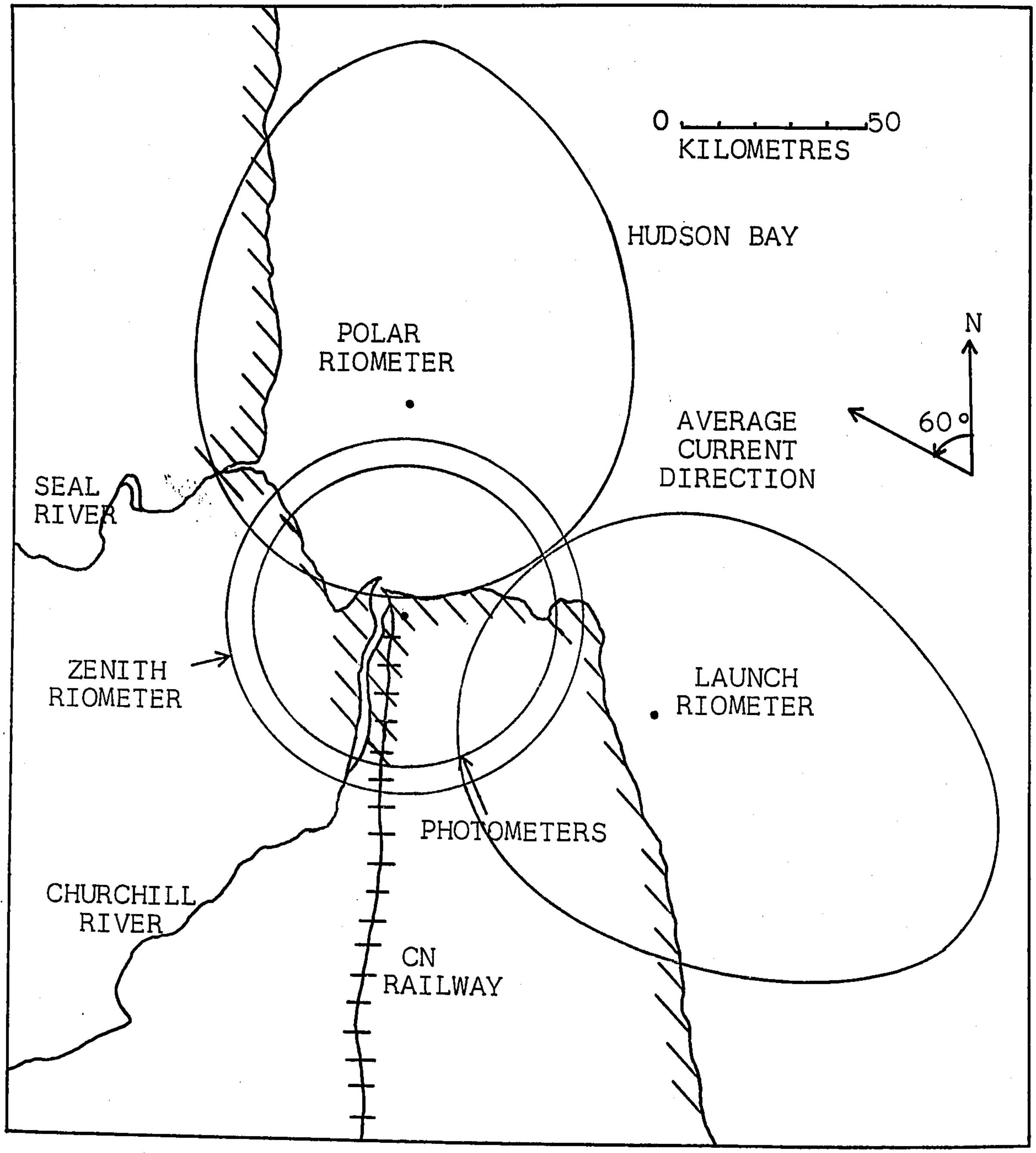
OBSERVATIONS AND RESULTS

7.1 CONDITIONS OF OBSERVATION

The sections following present and discuss measurements of luminosity and other auroral parameters made at Fort Churchill, Manitoba, at the end of March 1965. The geomagnetic latitude of Churchill is 68.8°N, and the corresponding L value is 8.

The auroral emissions measured were the 3914A band of N_2 1NG and the 5577A line of OI. The measurements were made in the zenith using ground-based photometers. The other auroral measurements used were magnetometer data, riometer data and all-sky camera pictures. Records from three 30 Mc/s riometers were available -- one pointed towards the zenith, one towards the pole and one along the rocket launch path above Churchill (Figure 9), but only the zenith data proved useful enough to be reproduced.

No account was taken of earth induction effects or of the earth's curvature when using the magnetometer data to calculate the position and strength of the line current, which was assumed to be at an altitude of 100 km for the purposes of distance calculations. Any error resulting from neglect of these effects is of little importance because the calculated quantities are used in a relative sense only.



Intersections of half-power points with 100 km level above Churchill.

FIGURE 9

RIOMETER AND PHOTOMETER FIELDS OF VIEW

All times given are Central Standard Time (CST) which is six hours behind Universal Time (UT). Geomagnetic midnight at Churchill for the period under discussion was calculated as 0106 by the method of Montbriand (1965). Geomagnetic midnight is derived for a dipole approximation to the earth's magnetic field and does not necessarily represent actual local magnetic midnight.

The term 'luminosity' is sometimes used in place of 'luminous flux.' In this case its use is effectively restricted to the 5577A line since the luminous flux is defined in terms of the lumen, basically a measure of visibility, and the 3914A band, being practically invisible in most auroras (Appendix), has almost zero luminosity. Intensity on the other hand is defined in terms of the Rayleigh, and therefore here denotes photon intensity. 'Luminosity' given in Rayleighs in this chapter applies only to the 5577A line, but the intensity given in Rayleighs is appropriate for either this line or the 3914A band.

Measurements of emission intensities in the zenith were made on six nights: the nights of 23/24 March to 30/31 March inclusive, except for the night of 26/27 March; and on the night of 5/6 April. On the nights of 29/30 March and 5/6 April no aurora was observed. On the night of 23/24 March, the auroral activity was high, but observations were disrupted by frequent power failures and equipment failures. This was also the case on the night of 24/25 March, but after 2315 on this night the activity disappeared anyway. On the three remaining nights (25/26, 27/28, 28/29 March) the auroral activity was moderate to high and data of reasonable quality were obtained. The events to be discussed occurred on these nights.

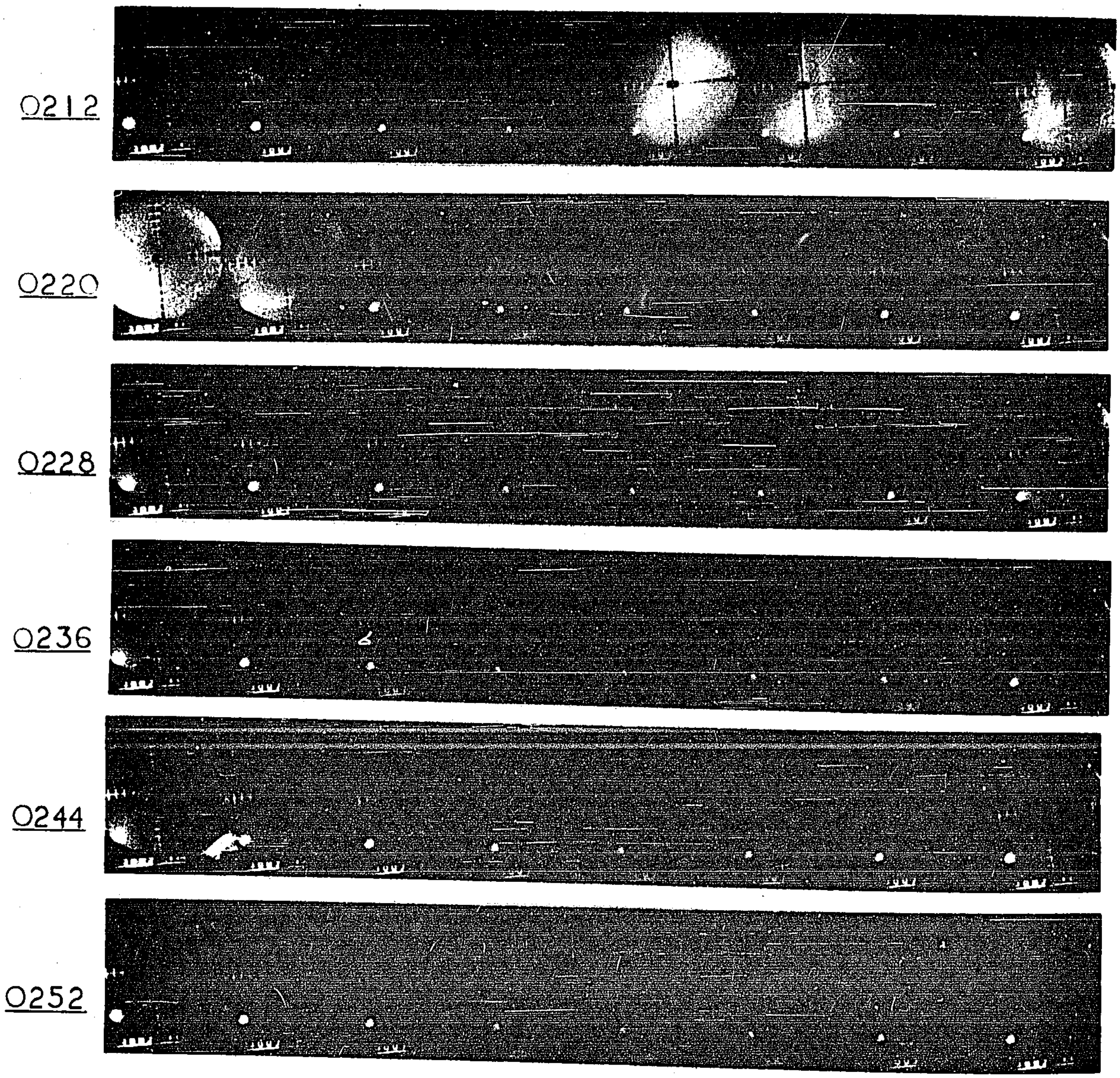
Photometric observations were, in general, made from about 2100 to 0400 (dawn), but selected events cover only an hour or so on each night. The reason for this is that the events were chosen because of some unusual feature, such as a large increase in intensity or intensity ratio, but at other times during these nights the aurora did not show any large variation in either of these quantities. To this extent, the events discussed here should not be regarded as typical of the general auroral activity.

Event A (characterized by a large increase in I(3914A)/I(5577A) during a diffuse glow) was selected initially because of its strong resemblance to some of the events discussed by Ansari (1964). A search of the records uncovered no other similar events. Similarly, Event C (exhibiting a large increase in I(3914A)/I(5577A) during a Class b corona) was the only one of its kind for which data were obtained. Events B, D, and E were selected in an attempt to see if a modified version of the Akasofu model, which seemed to fit some features of Event A, would be useful in explaining some of the results observed in these events.

Legible segments of the records of 23/24 March and 24/25 March were sampled at one- or two-minute intervals in an attempt to uncover any large changes in I(3914A)/I(5577A), but none were found. It is possible that short periods when this ratio was high might have escaped notice, because of the frequency of sampling and the breaks in the records. However, the general picture, from such data as are available, is that the ratio usually remains between 1.9 and 2.5, rarely increasing above 2.5 (excluding instances due to scattered light) and never falling below 1.9, during a display.

7.2 EVENT A 0200-0320 CST : 26 MARCH 1965

Event A began when a multiple band appeared overhead at 0216 and produced very intense luminosity (24 kR at 5577A) before dying down around 0218 (Figure 10). At 0220 the luminosity began to increase again but this time the aurora was a moderately intense (4 kR at 5577A) glow rather than a well-defined form, except for one small arc which appeared briefly at 0225. The intensity of the glow began to fade after 0240 and more quickly after 0250. By



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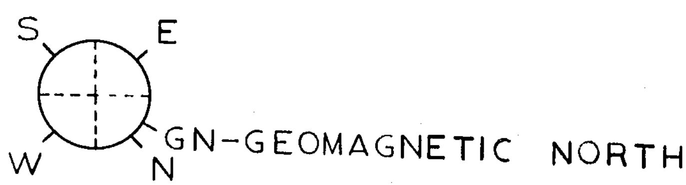
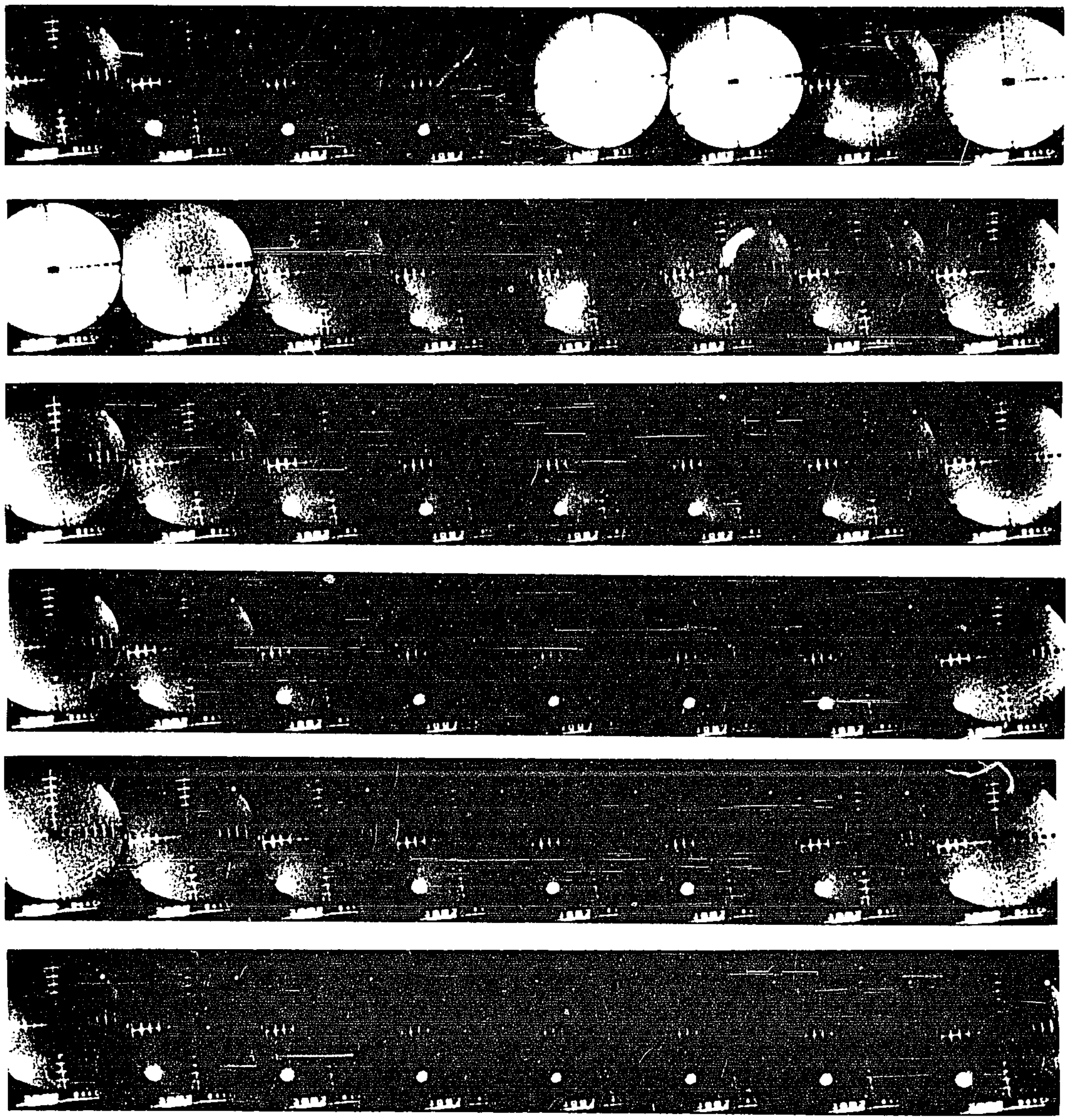


TIME
CST

FIGURE 10. ASC PICTURES FOR EVENT A, 26 MARCH.



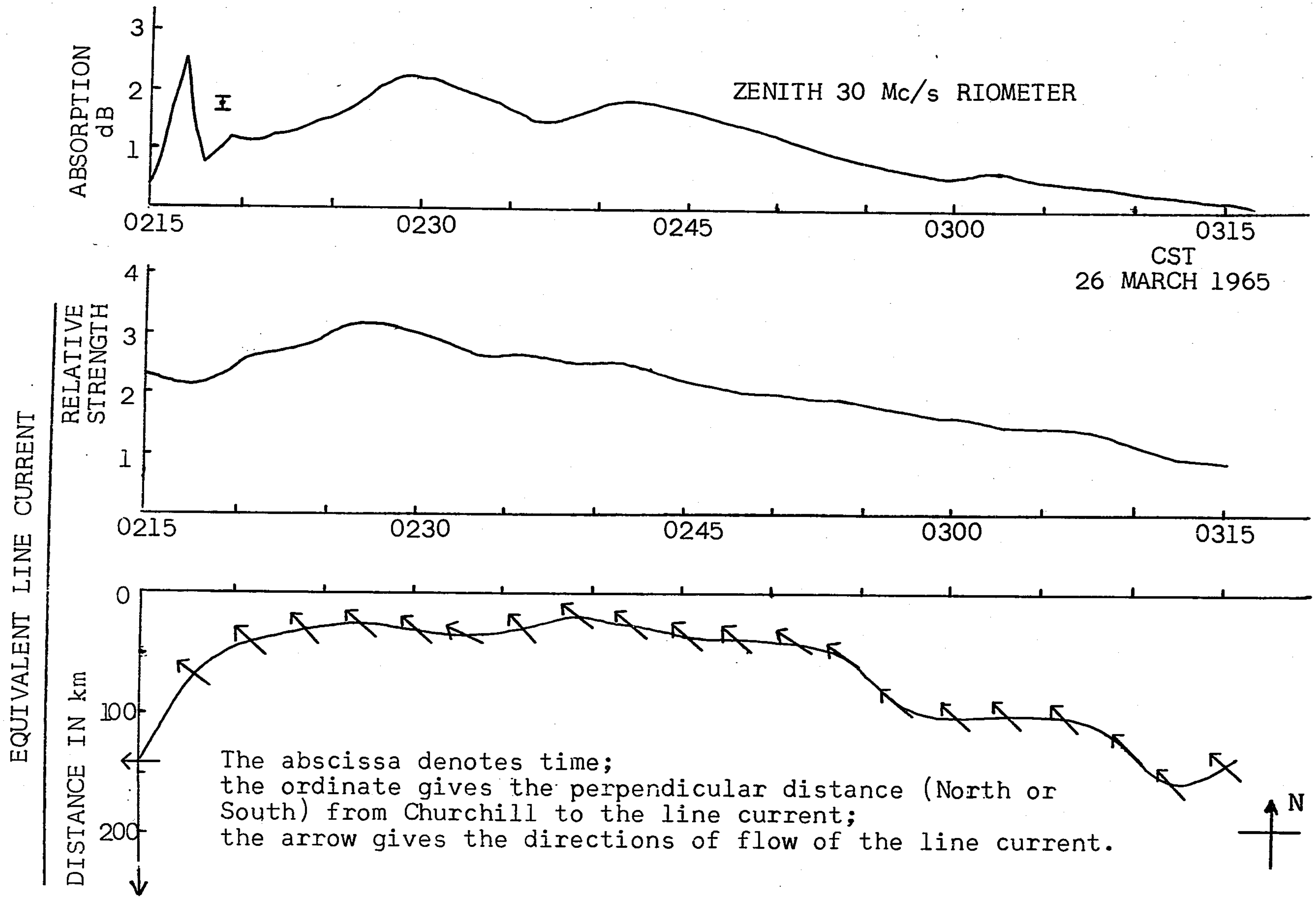


FIGURE 11

MAGNETIC AND RADIO ABSORPTION DATA FOR EVENT A

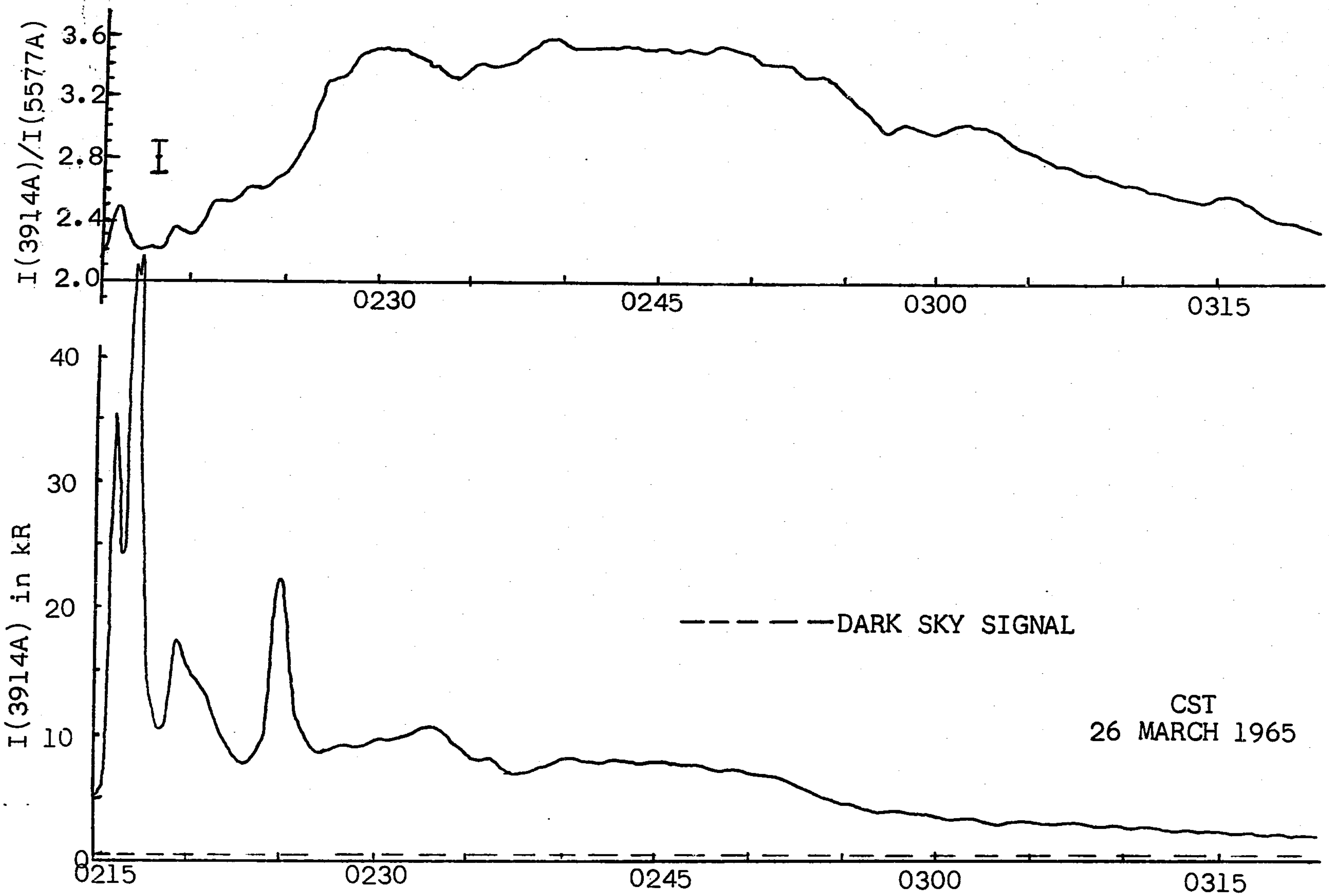


FIGURE 12

INTENSITY AND INTENSITY RATIO DATA FOR EVENT A

0320 the auroral activity had died down completely.

Zenith riometer absorption during the event (Figure 11) took the form of a sharp spike of 2.5 db when the initial multiple band was overhead. Following the recovery from this spike the absorption gradually increased again to reach a maximum of 2.2 db at 0230, during the period of diffuse visual aurora. A decrease in the absorption which occurred at 0237 did not seem to be associated with any features of the other parameters. A final slow decrease to zero absorption took place between 0241 and 0330.

The equivalent line current (Figure 11) remained south of Churchill throughout this event but approached rapidly during the initial luminosity peak at 0215, and more slowly after that. It came closest (to about 20km) at 0239 and remained in that region until 0255 when it began to withdraw to the south again, reaching a distance of 140 km by 0315. The behaviour of the current around 0215 was that of a westward surge but there was no surge activity after that.

The intensity ratio R of the 3914A band and the 5577A line (Figure 12) did not change (R was about 2.3 within the computation uncertainty) during the initial luminosity increase, or 'break-up,' but about seven or eight minutes later R began to increase slowly and reached a maximum of 3.5 (50% above normal) at 0240. This is taken to mean that no significant change in the electron spectrum above about 25 keV (Section 4.5) occurred during the break-up, which is equivalent to the expansive phase of an Akasofu substorm. On the other hand, the onset of the diffuse glow was associated with a spectral hardening, as evidenced by the increase in R (Section 4.5), and this hardening is apparently linked also with the approach of the line current from the south, while the visual northern border of the aurora was far to the north at this time. Similarly during the period 0250-0255 the decrease in R was associated with the withdrawal of the line current into the south.

This behaviour supports the findings of Clark and Anger (1966) that the region of intense X-ray production (that is, of harder electron spectrum) is closely associated in space with the line current, while the visual northern border on occasion is quite separate from both. In this case however all three of these regions did not move northwards together during the expansive phase, since the visual northern border and the line current did not coincide.

In agreement with the interpretation given above, Ansari (1964) concluded from a study of several similar events that the long slowly-changing hump of absorption (his Category 2) and the reduced luminosity were caused by a hardening of the electron spectrum. Similarly in the present Event A the absorption during the diffuse

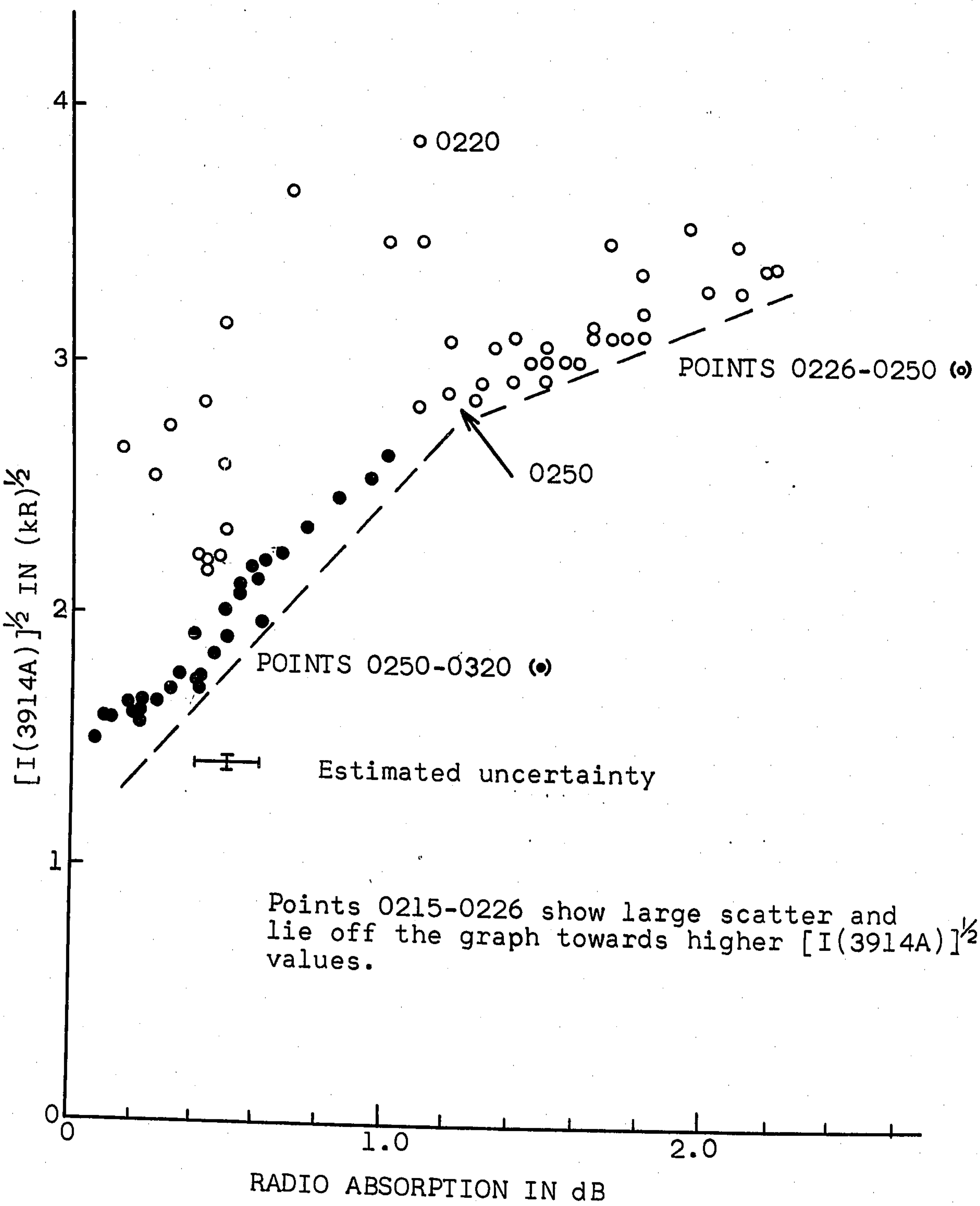


FIGURE 13

EVENT A:
GRAPH OF $[I(3914A)]^{1/2}$ vs RADIO ABSORPTION

glow was almost as great as that during the break-up, but the luminosity was a factor of 5 less during the glow than during the earlier period. However, this could quite possibly have been caused by the dependence of riometer measurements on the area of the absorbing region (Section 2.2.2).

Following Johansen (1965) the square root of the 3914A intensity was plotted at one minute intervals as a function of absorption (Figure 13). As expected, the dependence of riometer readings on the areal extent of absorption in the field of view caused the points between 0215 and 0225 to show a large scatter, but always in the sense that the emission/absorption ratio was larger, rather than smaller than for most other points. After 0225 the aurora was diffuse and widespread and hence the plotted points are more orderly.

The striking feature of Figure 13 is that the plotted points during the period of high R, that is from 0225 to 0250, form a line of lesser slope than the points after 0250, when R began to decrease to normal again. The changeover occurs between 0250 and 0251 and is thus quite sudden, and indeed it is more marked than the corresponding changes in the magnetic field or in R. A similar definite change of slope in the line was found by Johansen (1965) but the time resolution of his data was such that he could say only that the change occurred in less than 15 minutes. The changes he studied did not appear to be associated with any particular time of the night, and occurred on only about half of the nights studied.

The form of the plot in Figure 13 is consistent with the removal at 0250 of an energetic electron component from the spectrum, since the change is apparently continuous and quite marked. The high emission rate for 'zero' absorption (a similar result was found by Johansen) may be an indication of an unchanging very soft electron component, capable of causing 3914A emission (1.7 kR) but not abosrption. It could also be associated with airglow emission; if airglow is always present the apparent 'zero absorption' luminosity does not show definitely that emission can occur without absorption. This is because the absorption of radio noise is measured with respect to the normal quiet-day noise signal, which may suffer a permanent but small amount of absorption associated with airglow. An equivalent statement is that the absorption figures given are, say, 1 db too low (because the assumed baseline of the record is too high), but that this error is constant and practically always present in all absorption measurements at the same location.

7.3 EVENT B 2255-2400 CST 27 MARCH 1965

ASC pictures (Figure 14) and magnetometer data (Figure 15) indicate that a surge or loop passed westward between 2250 and 2300 and the resulting luminosity burst was fading when photometer observations began at 2255. This event therefore covers the recovery phase of a substorm rather than the expansive phase, and views it from a point well to the west of magnetic midnight break-up. It exhibits some interesting differences from Event A in the application of the Akasofu model.

Magnetometer data in particular show that the line current crossed northward overhead at 2250 and reached a maximum distance to the north of 250 km at 2300. From 2310 to 2330 the current stayed between 20 and 70 km north, and following a slight diminution and movement of 200 km into the north around 2340 the current finally returned into the south at 2400. This shows that throughout this event Churchill was south of the line current. In addition, ASC pictures show some activity at all times near the northern horizon, indicating that the visual northern border was also north of Churchill.

An absorption peak of 1 db (Figure 15) occurred at 2300 in association with a 3914A intensity of 41 kR, and at 2308 a peak of 0.7 db was associated with a 3914A intensity of 48kR (Figure 16). This may indicate that a harder

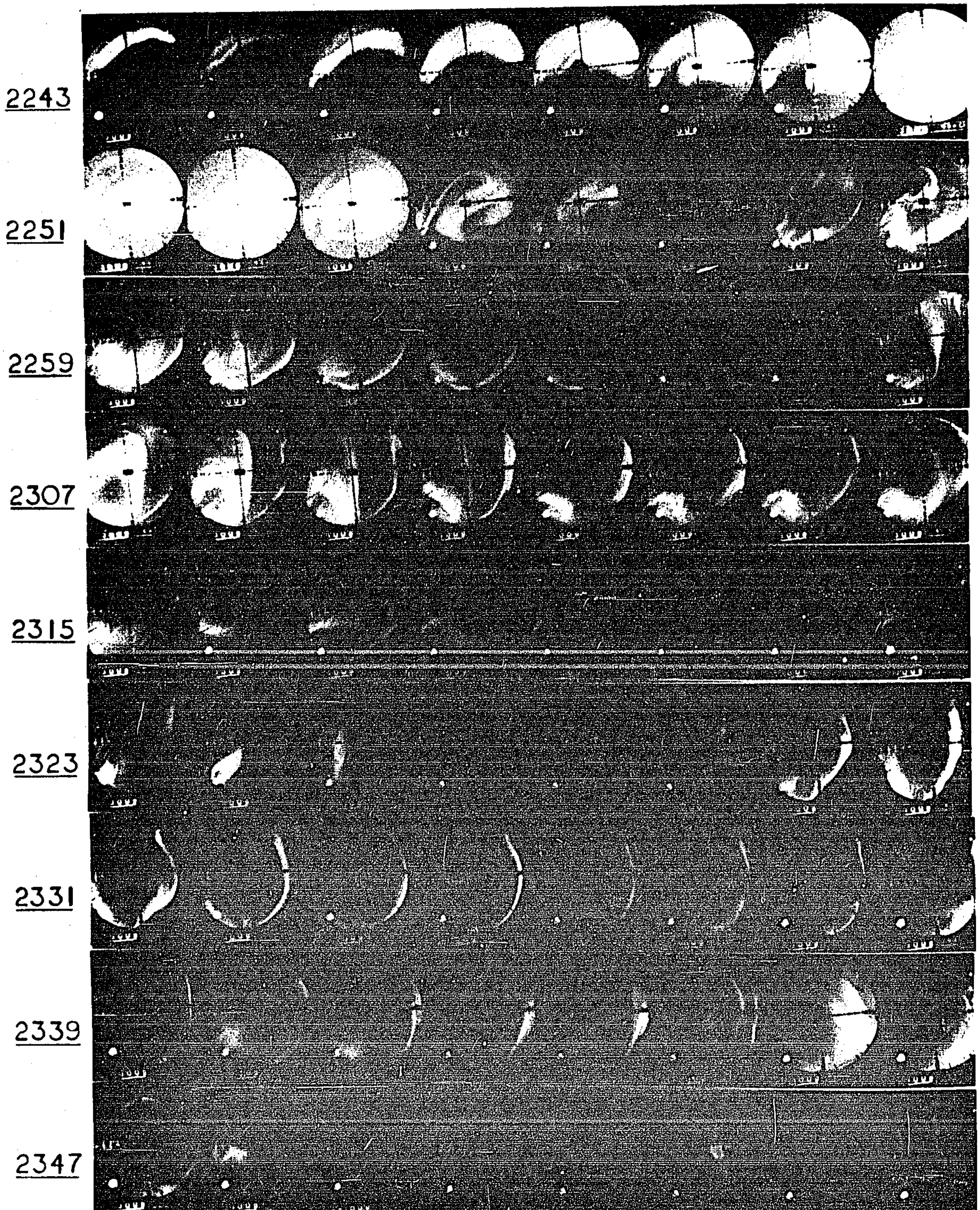
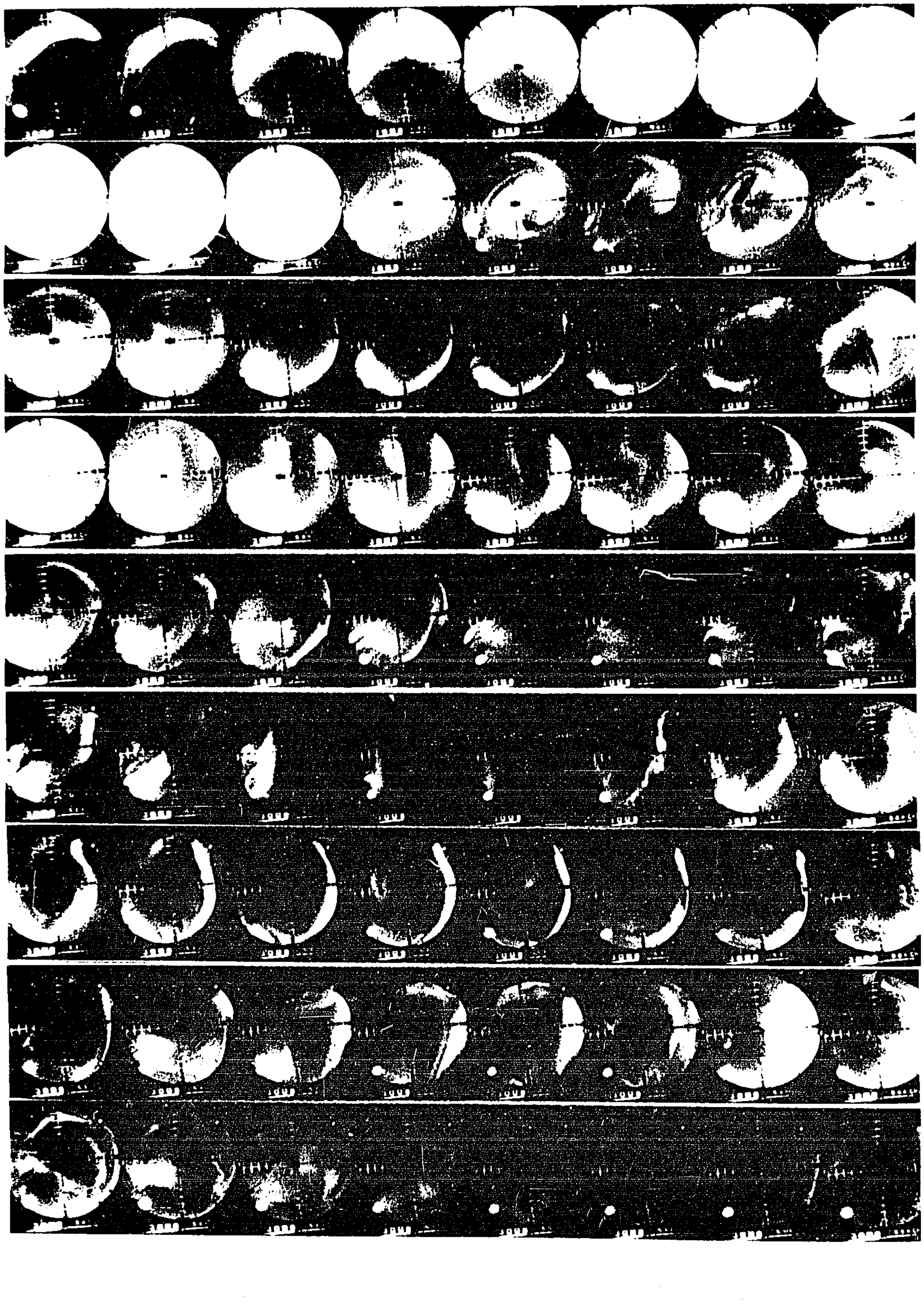


FIGURE 14. ASC PICTURES FOR EVENT B, 27 MARCH.



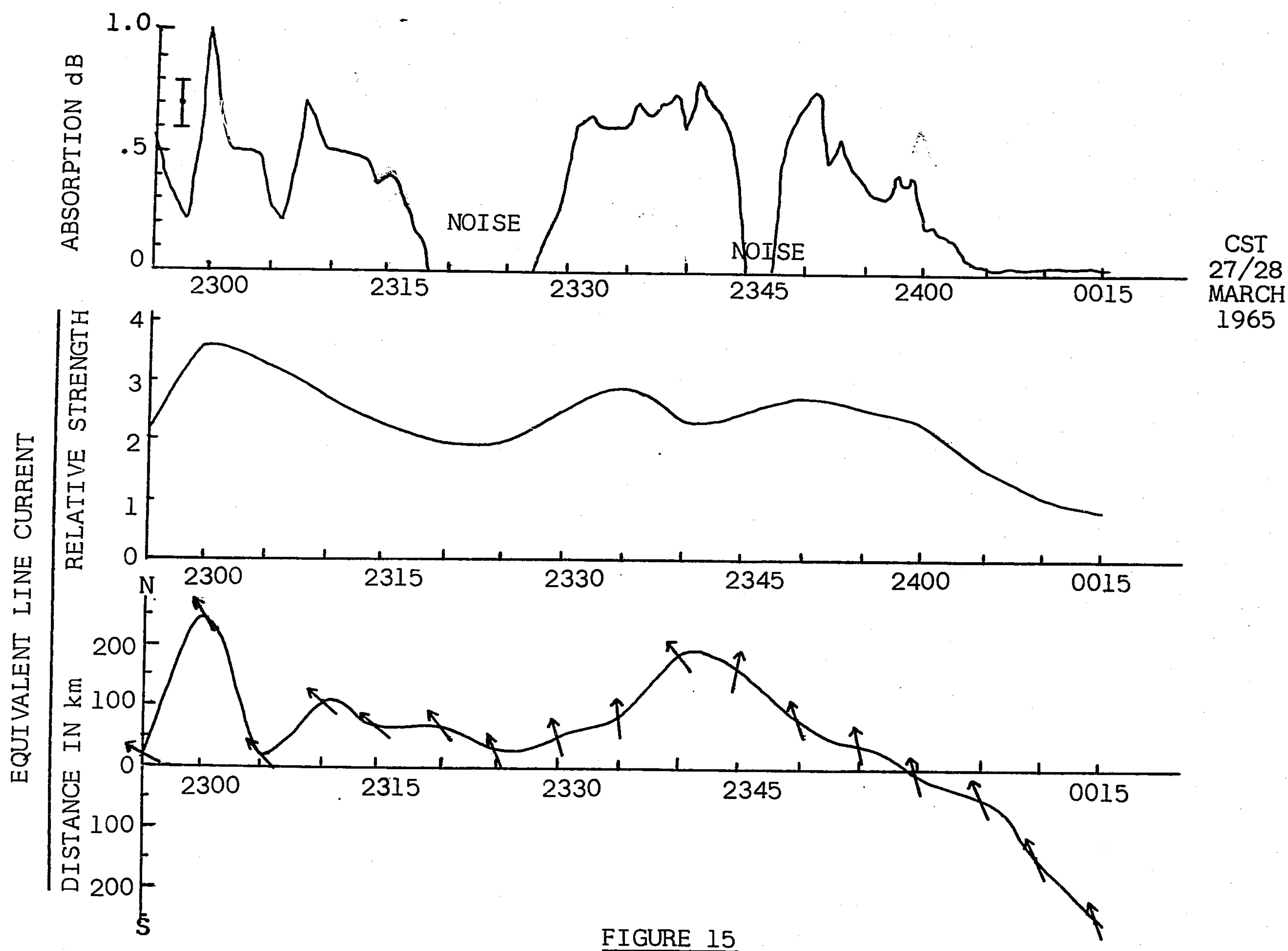


FIGURE 15

MAGNETIC AND RADIO ABSORPTION DATA FOR EVENT B

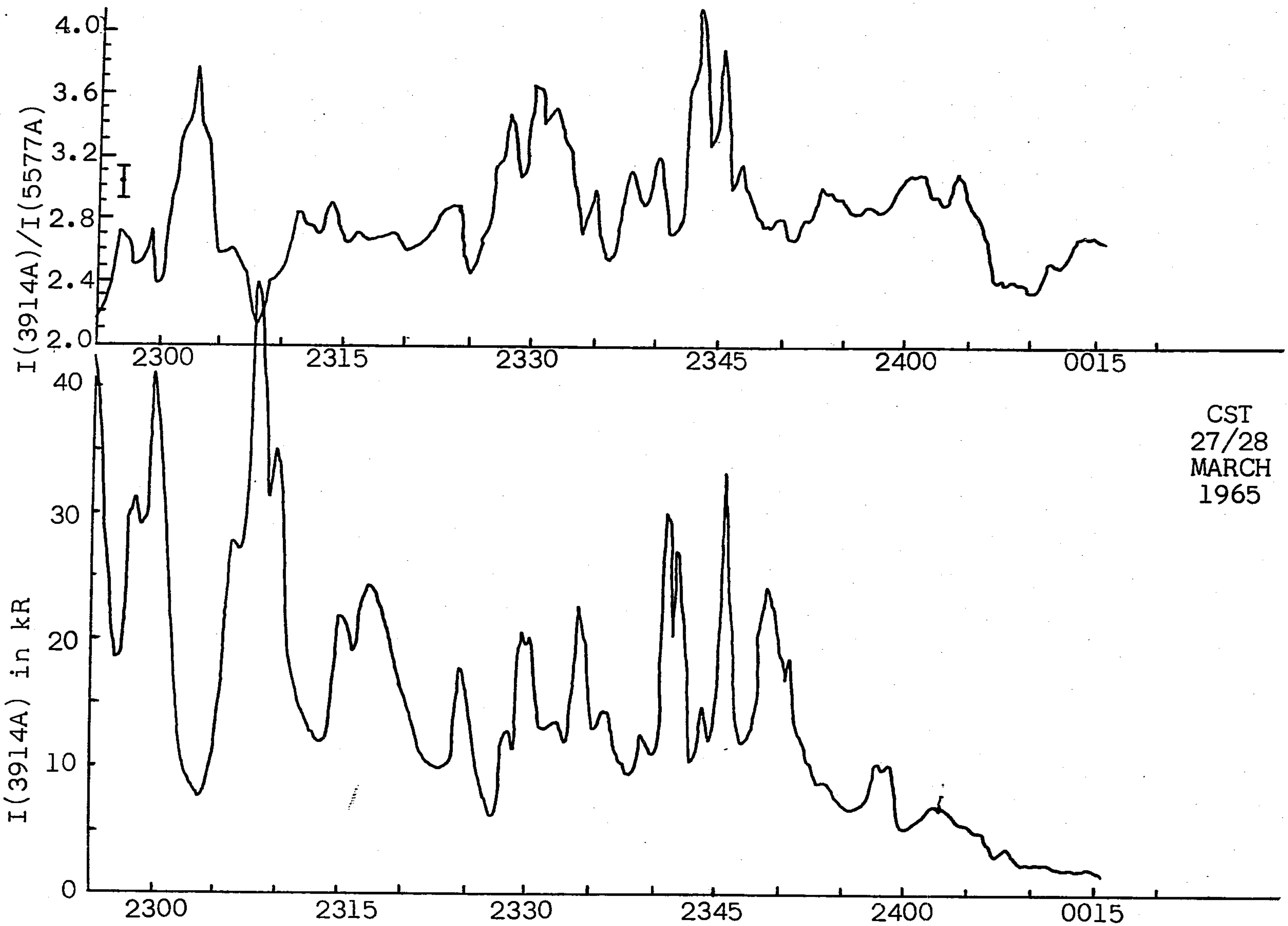


FIGURE 16

INTENSITY AND INTENSITY RATIO DATA FOR EVENT B electron spectrum caused the first peak, and in fact R was about 15% greater at 2300 than at 2308. However since the aurora in each case consisted of discrete forms rather than diffuse glows it might be held that the spectral change indicated by the riometer results was an apparent one resulting from the dependence of radio absorption on the distribution of the absorbing areas. Throughout the remainder of Event B the absorption was around 0.4-0.7 db almost continuously, and showed a very rough correlation with luminosity peaks.

Owing to the complicated structural development of the auroral bands during this event, it is difficult to say with certainty what the real behaviour of R was. However, inspection of the ASC records indicates that increases due to scattering could be expected from 2301 to 2305, with very strong scattering at 2302, 2303 and 2304. Similarly, scattered light would increase the R value between 2311 and 2314, 2320 and 2323, 2325 and 2330, and would have lesser influence throughout the rest of the event. In addition, R values obtained when I(3914A) was small cannot be regarded as being highly accurate and any short periods with high R value and low I(3914A), occurring just before periods with high I(3914A) and low R, are also suspect.

The minimum R value during periods of high I(3914A) was 2.1 at 2255, 2.3 at 2300, 2.1 at 2308, and 2.5 at 2341. Other R values which might be considered fairly reliable were 2.6 at 2315 to 2320 and 2.3 at 2325. There is thus some evidence that increases of up to 25% above the minimum R value may have occurred, but the value of R at any time seemed quite variable (even apart from scattering), indicating a much more variable electron spectrum than in Event A, in which R showed only one large increase and one decrease back to a lower value.

In contrast to Event A, then, Event B covers a period when the line current and the visual northern border both remained north of Churchill. The region of low energy electron precipitation may again have been separated spatially from the region of high energy electron precipitation, as in Event A, but Churchill was not suitably situated for observing very large or prolonged spectral changes as the two regions moved north and south. If this view is correct, a station, say, 100 km north of Churchill might have observed large changes in R during this event, but at Churchill and points south, photometric indications of spectral variations would be rather chaotic, and not very large, both because variations in the low energy (1-24 keV) electron range have little effect on R, and because the luminosity produced by the low energy electrons would overwhelm the changes in R caused by changes in the distribution of high energy (30-100 keV) electrons.

7.4 EVENT C 0100-0110 CST 28 MARCH 1965

In contrast to Events A and B, where a modification of the Akasofu model agreed fairly well with the data, the model does not seem to be of much help in understanding the development of Event C, although it does fit with some features of the data. In spite of this, Event C is still quite significant, as Class b aurora was reported twice and it is possible that these two cases may exemplify the two types of displays with red lower borders, suggested in Chapter Five. The period of the event coincides with geomagnetic midnight.

From 0041 to 0055 ASC pictures (Figure 17) show an east-west band stretching from the eastern horizon to 80° elevation in the west and passing slightly north of the zenith. At 0051 a group of poorly defined bands or patches approached from the south-west, and at 0100 one of these patches brightened and extended to the zenith by 0101. Faint Class b aurora was reported at this time. The eastward extension continued until 0105 when the band moved into the far north. At 0107 a rather diffuse band approached from the south-west and moved to the zenith by 0108, when a brilliant Class b corona was reported overhead. The luminosity of this corona, judged from the ASC picture, was not particularly great; the contrast between this observation and the outside observer's

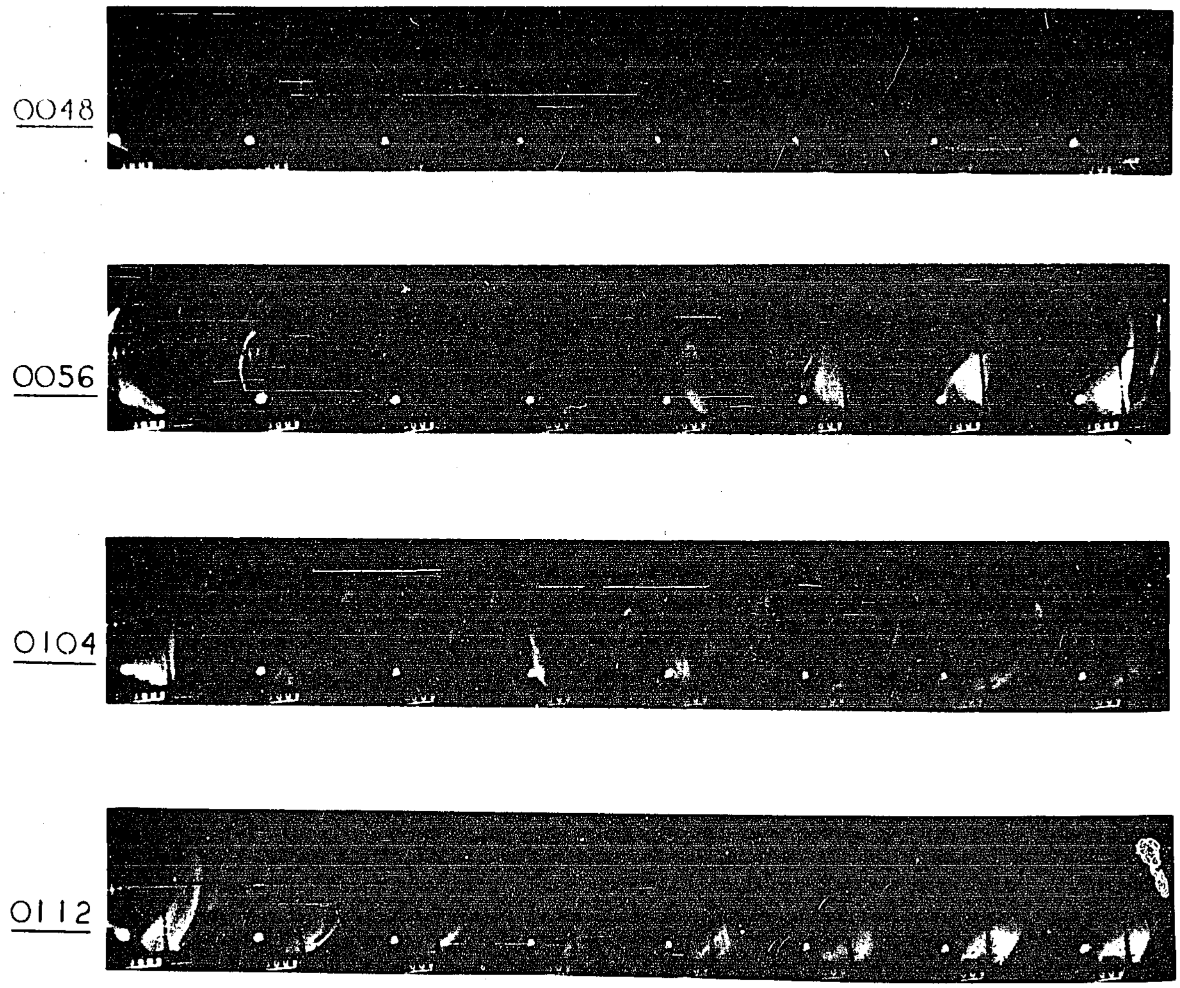


FIGURE 17. ASC PICTURES FOR EVENT C, 28 MARCH.

… 12 … A … TURES FOR EVENT , … MARCH.

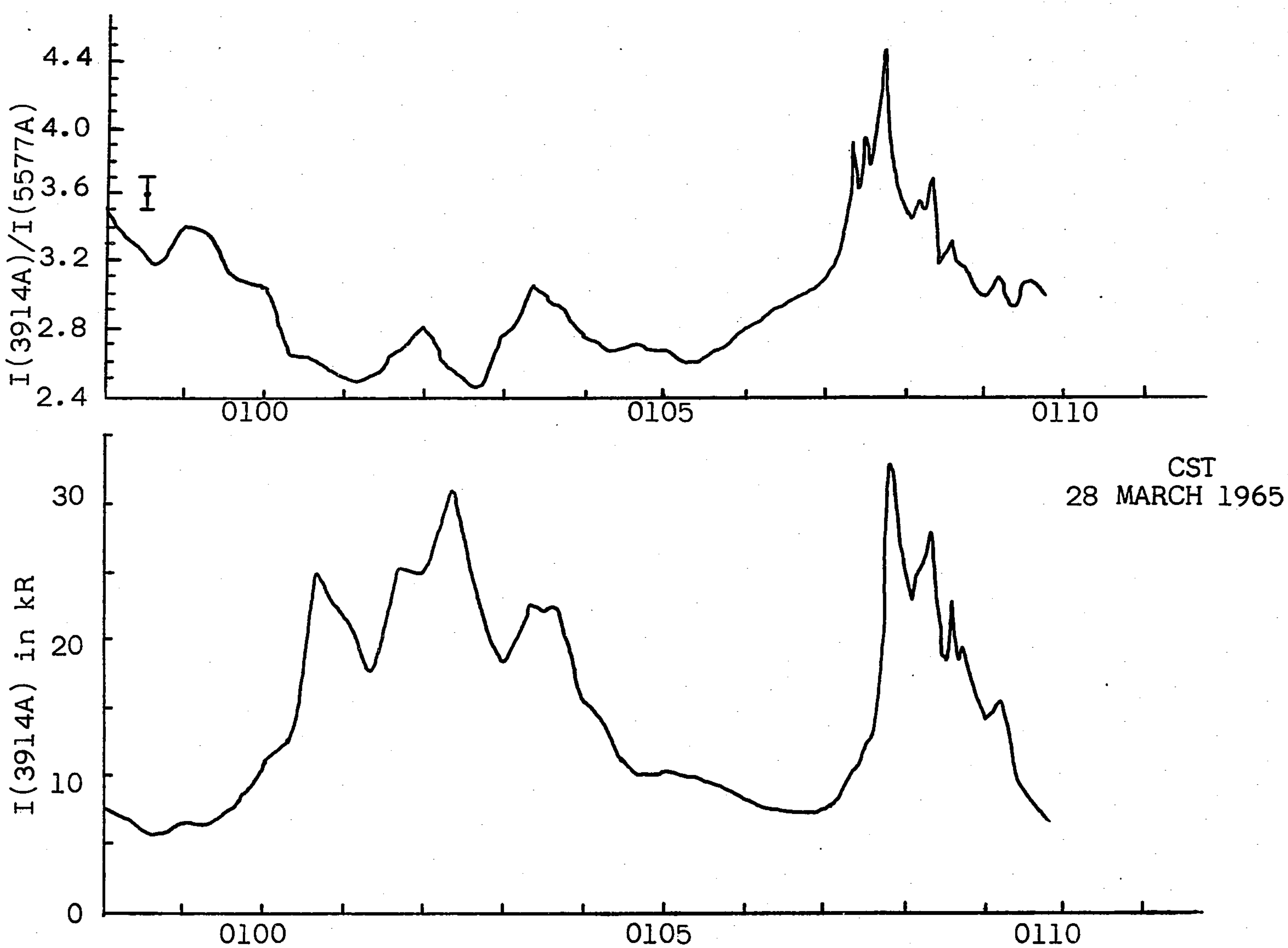


FIGURE 18

INTENSITY AND INTENSITY RATIO DATA FOR EVENT C

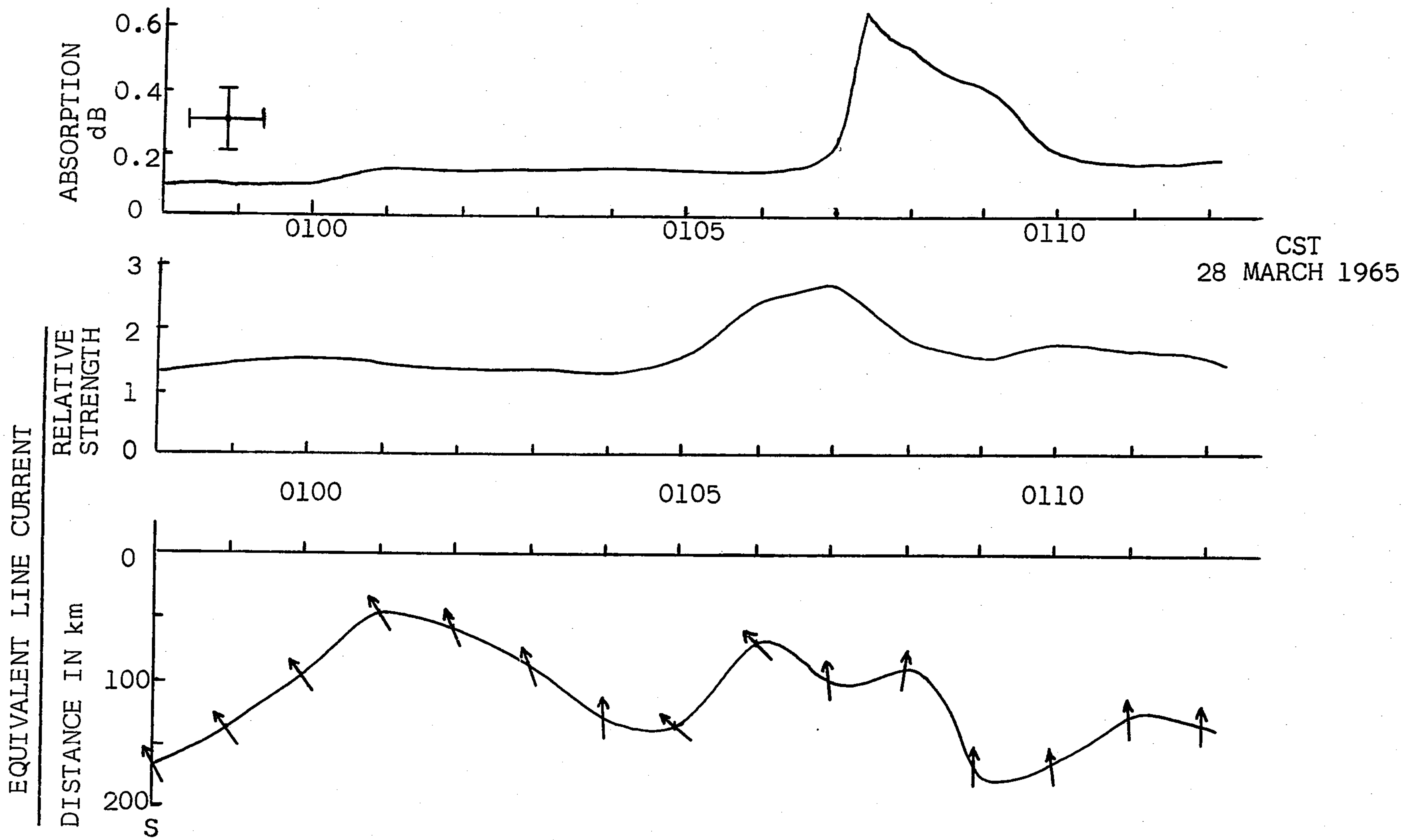


FIGURE 19

MAGNETIC AND RADIO ABSORPTION DATA FOR EVENT C impression of brilliance was probably caused by the psychological impact of red. I(3914A) at this time (Figure 18) was 33 kR, which is fairly high, but even this would not be expected to contribute much luminosity (Appendix). The ASC picture for 0108, with its 15 second integration of movements in the corona, shows a patchy form in the zenith. At 0109 this had died out and the aurora was confined to a band at 20° elevation along the northern horizon, which broadened and moved south to 30°-80° elevation in the north at 0112, and after that it gradually moved off to the west.

Magnetometer data (Figure 19) indicate that the line current during this event stayed well south of the station. It approached to a distance of 50 km at 0101, but after that did not come closer at any time than 70 km. During the Class b corona the current system was about 80-100 km to the south and thus appears to have had little direct connection with this display. On the whole the record is consistent with the motion of a westward surge starting at 0105 and ending at 0115, which reached its most northerly position at the time of or just before the Class b corona. This westward surge does not, in the Akasofu model, fit very well with the apparent eastward drift of the auroral luminosity which was observed around the beginning of the event.

Riometer absorption during the event (Figure 19) did not show any features of unusual interest. The Class b corona was associated with 0.6 db, and by 0110 the absorption had fallen to 0.2 db, and this level was maintained for about an hour afterwards.

The behaviour of the ratio R is quite significant, the most obvious feature being an increase in R of almost 100% (to a value of 4.5) when the Class b aurora at 0108 occurred. On the other hand, the faint Class b aurora reported at 0101 caused little or no change in R (which was about 2.5 at this time), even though the 5577A luminosity in that case was slightly greater than at 0108. It seems probable that the Class b display at 0108 was caused mainly by a marked hardening of the electron spectrum above about 25 keV, while there was little change in the flux of electrons below that energy, and the colour reported at 0101 arose as a result of an overall increase in the flux with no spectral change. The electron spectrum must have been fairly hard in the first place, however (see Section 5.3). This is perhaps supported by the fact that the minimum value of R was 2.5, whereas the lowest value observed in any Event was 1.9. The flux increase was great enough to enable the red emission predominance at low altitudes to become visible, but the flux of high energy electrons was not great enough to provide a spectacular burst of red. (The band at 0101 was brighter than the luminosity figure indicates since the field of view was not filled by the band.) If correct, this conclusion would support the predictions of Chapter Five.

At no time during this event was the visual northern border associated in space with the line current. This represents a marked difference from Events A and B, in which the line current and the visual northern border seemed to be close together at the beginning of the expansive phase. In Event C it is difficult to associate the visual records, at least, with the idea of an expansive phase, and thus in this case a good fit does not seem to have occurred between the Akasofu model and the display.

7.5 EVENT D 2240-2350 CST 28 MARCH 1965
EVENT E 2350-0050 CST 28/29 MARCH 1965

The period 2150 to 0200 on this night affords a good opportunity of examining how the Akasofu model agrees with auroral observations. Within this time there were two substorms (Events D and E) which probably overlapped slightly in time. These two events will be examined as a unit before being dealt with separately.

One feature which stands out on the ASC pictures (Figures 20,23) for this period is the stability of the 'normal' quiet arc system. An arc appeared on the eastern horizon at 2152 and within two or three minutes had extended to the WNW horizon, passing north of the

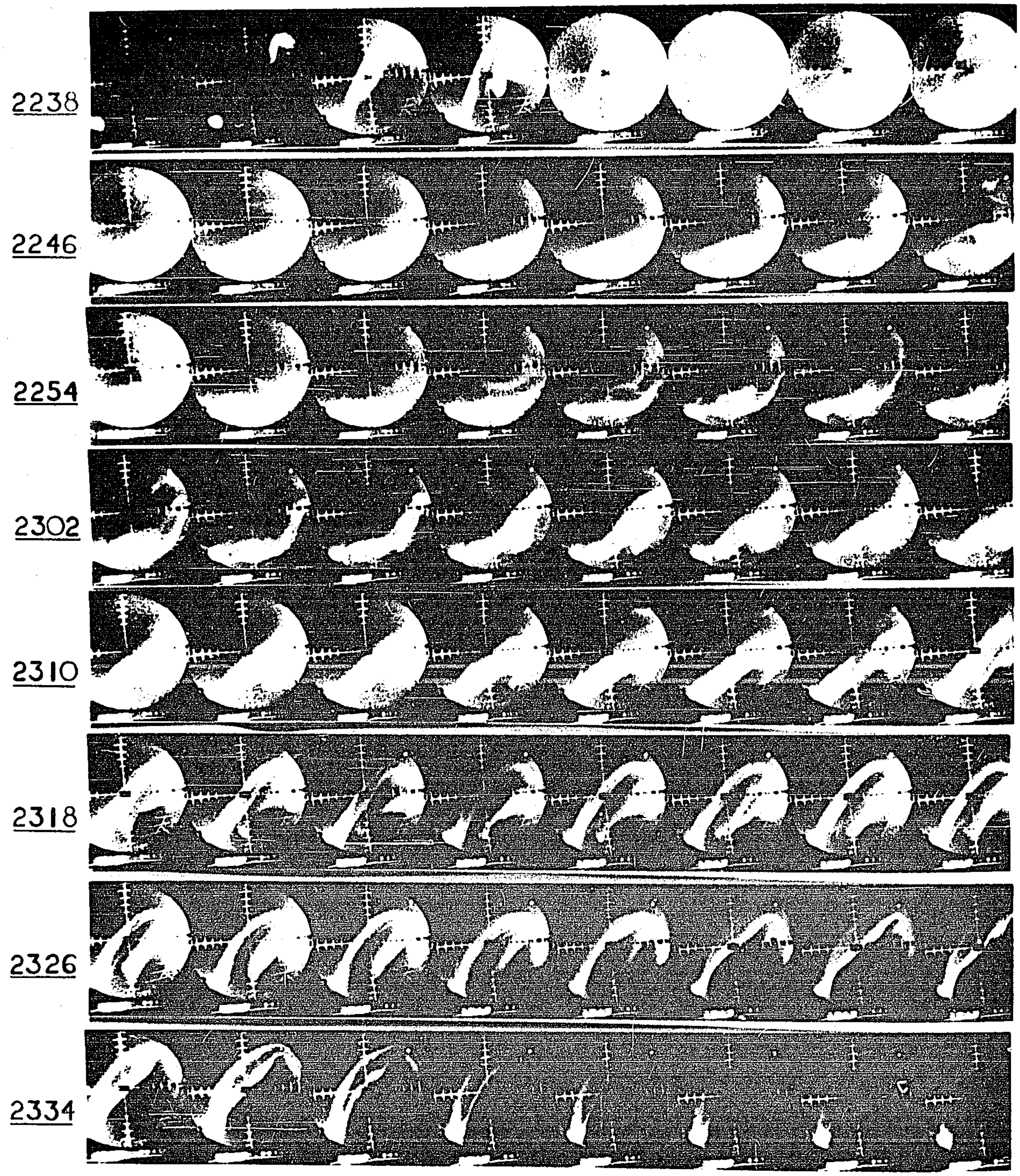


FIGURE 20. ASC PICTURES FOR EVENT D, 28 MARCH.

[illegible] EVENT [illegible]

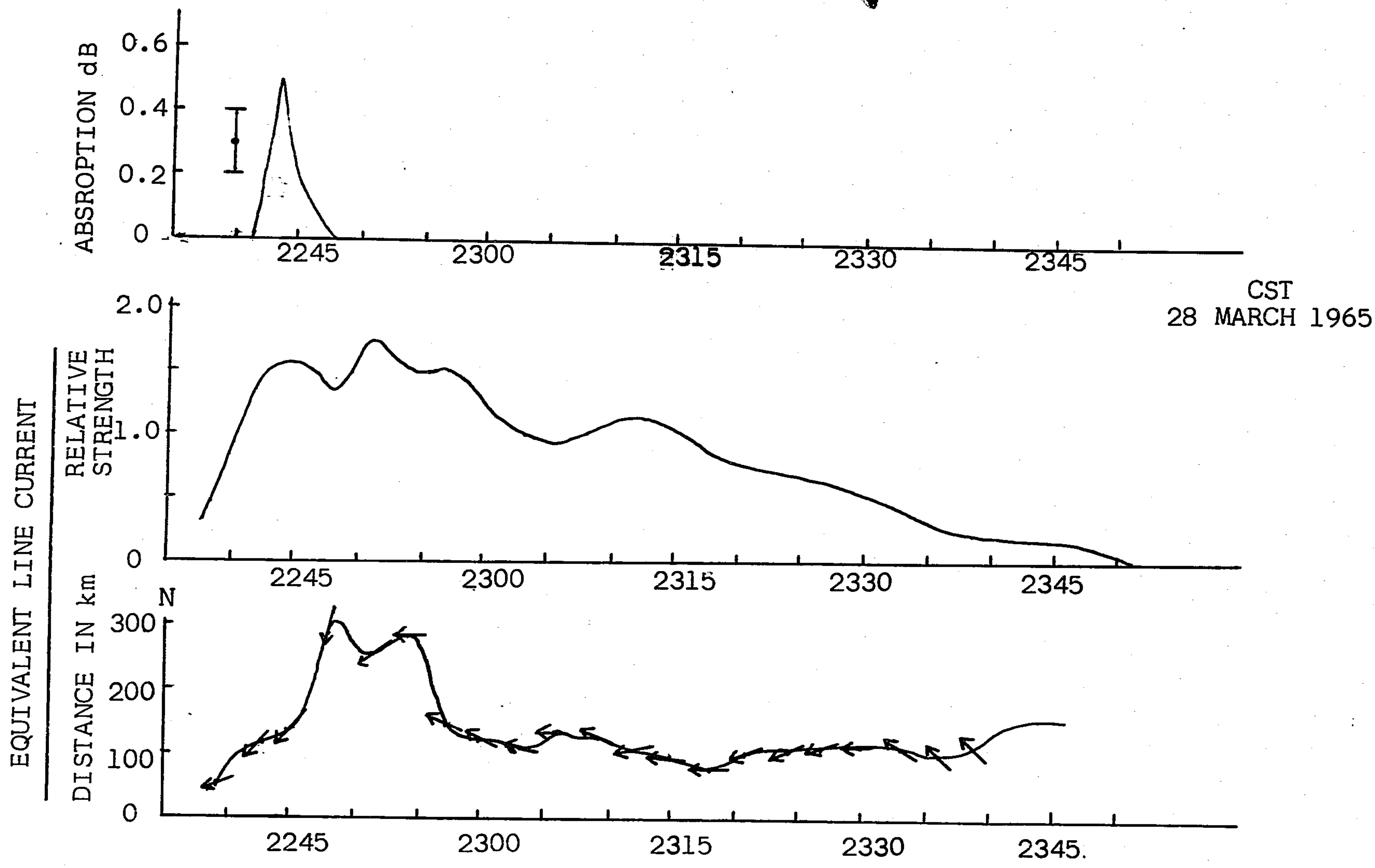


FIGURE 21

MAGNETIC AND RADIO ABSORPTION DATA FOR EVENT D

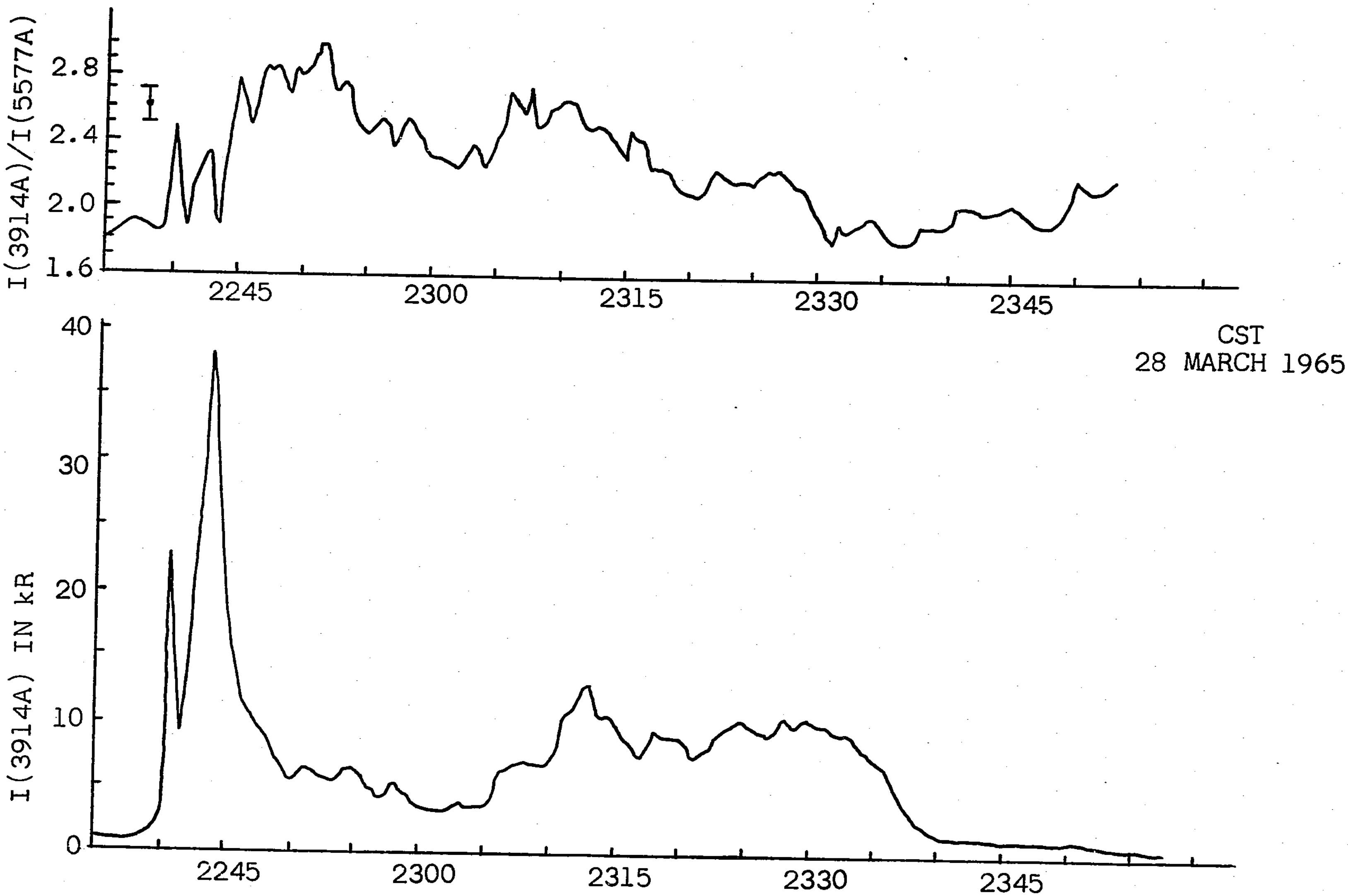


FIGURE 22

INTENSITY AND INTENSITY RATIO DATA FOR EVENT D zenith at about 80° elevation. Almost no changes in the position or luminosity of this arc occurred until 2215, when it became very faint and just barely visible to the camera, but even then no change in its position occurred until the onset of Event D at 2240, when severe disruption and loop distortion took place. Further distortion and dislocation of the system also occurred throughout Event E (2350-0050) but by 0055 a diffuse band had taken up almost the same position as the arc of 2152-2215. While its position was not quite as well defined as that of the original arc, this band did not suffer any further disturbance and remained in the 'equilibrium' position until it faded out of sight at around 0200. This tendency of the aurora to have a stable form consisting of quiet arcs is one of the features noted by Akasofu (1964).

7.5.1 Event D

Event D began with the appearance of a surge at the eastern end of the quiet arc at 2239. At 2240 the associated luminosity had propagated as far as the western horizon. In the ASC pictures following that time the surge activity and luminosity increased, chiefly in the northern half of the sky and the zenith. By 2246 most of the activity was at 30° elevation in the north-west sector of the sky, where loop structure was distinguishable until 2250. From 2250 to 2305 a distorted band returned to about 70° elevation in the north-west. Some further loop distortion occurred between 2315 and 2330. After 2335 the display moved south of the zenith, reaching 60° elevation in the south at 2345 and 40° elevation at 2350, also in the south.

The magnetometer (Figure 21) showed the leading edge of a westward surge passing just north of Churchill at 2239 and after that the current stayed north of the station until 2345. At this time the trailing edge of the same surge approached from the east but the current system had died out before the surge edge passed overhead. The arrival of the leading edge of the surge north of Churchill coincided closely in time with an increase in the total current strength. At the start of this event, then, the line current and the visual northern border were both a little to the north of Churchill, but at the end of the event the visual northern border was slightly south of Churchill while the line current did not pass south until about 10 minutes later. Because of the small size of the magnetic deflections at these times, no accurate estimates can be given for the line current's position but it appears likely that the visual northern border and the line current were within about 50 km of each other when both were near Churchill.

Because of this close association between the current and the northern border, resulting in little spatial separation of the high- and low-energy electron precipitation regions, one might expect that no large changes in R (Figure 22) occurred during this event. There is in fact a 30% increase in R between 2245 and 2255, but inspection of the ASC pictures shows that there was little luminosity in the field of view of the photometers at this time, with a large patch of bright aurora just out of view, so this change in R is very probably an apparent one resulting from light scattering.

The view that little spectral hardening occurred in Event D is supported by the riometer records (Figure 21), which show that absorption occurred only during the most intense luminosity bursts. The zenith riometer recorded a short spike of 0.5 db at 2243, when the 3914A intensity was 38 kR. This seems a rather low absorption figure for this emission intensity, and indicates that the electron spectrum was perhaps quite soft. On the other hand, the low reading may have resulted simply from the fact that the absorption did not fill the field of view of the riometer.

On the whole, Event D seems to have been an event in which there was little separation of the high- and low-energy electron precipitation regions, as indicated by magnetometer and ASC records. Some support is provided

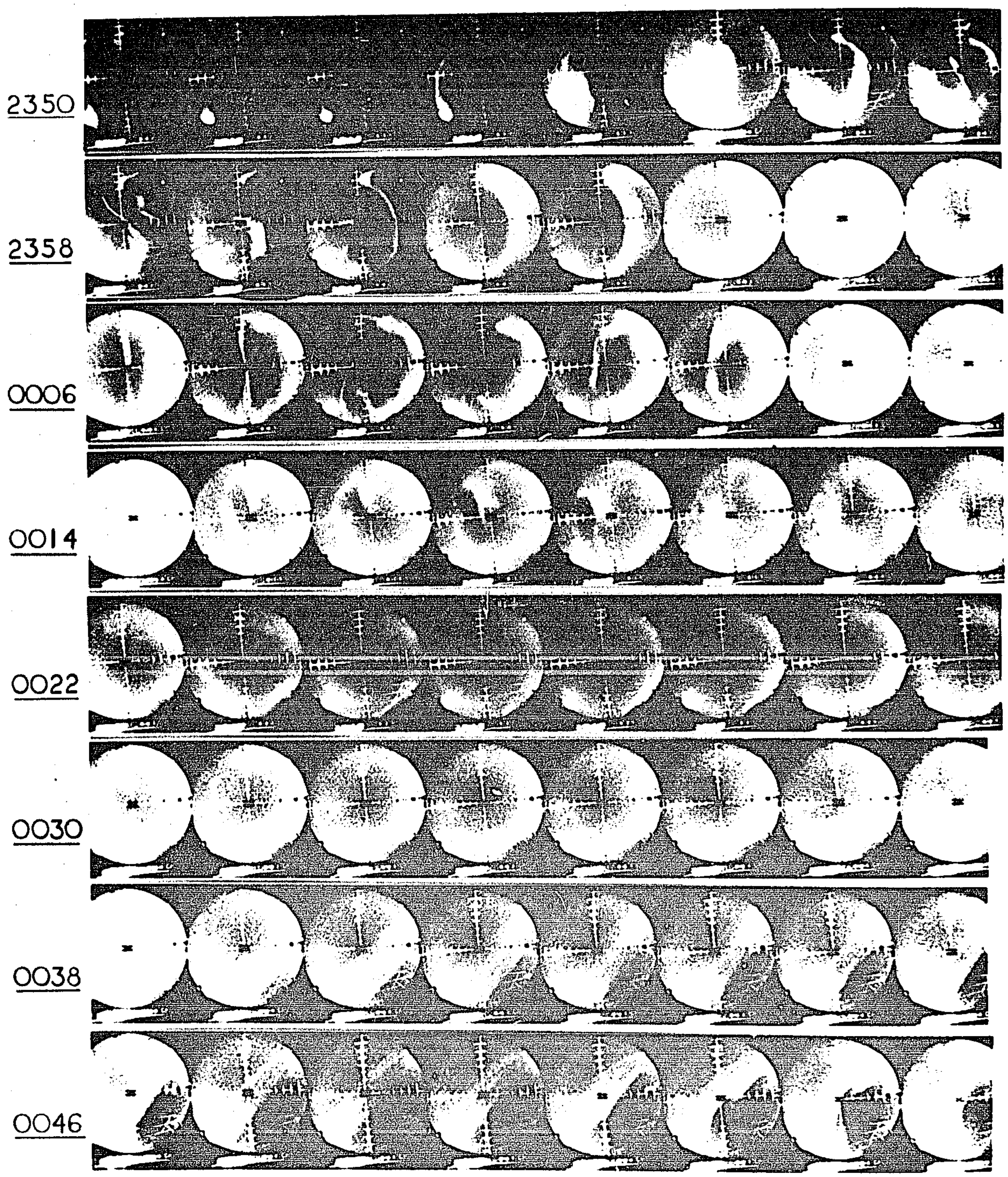


FIGURE 23. ASC PICTURES FOR EVENT E, 28/29 MARCH.

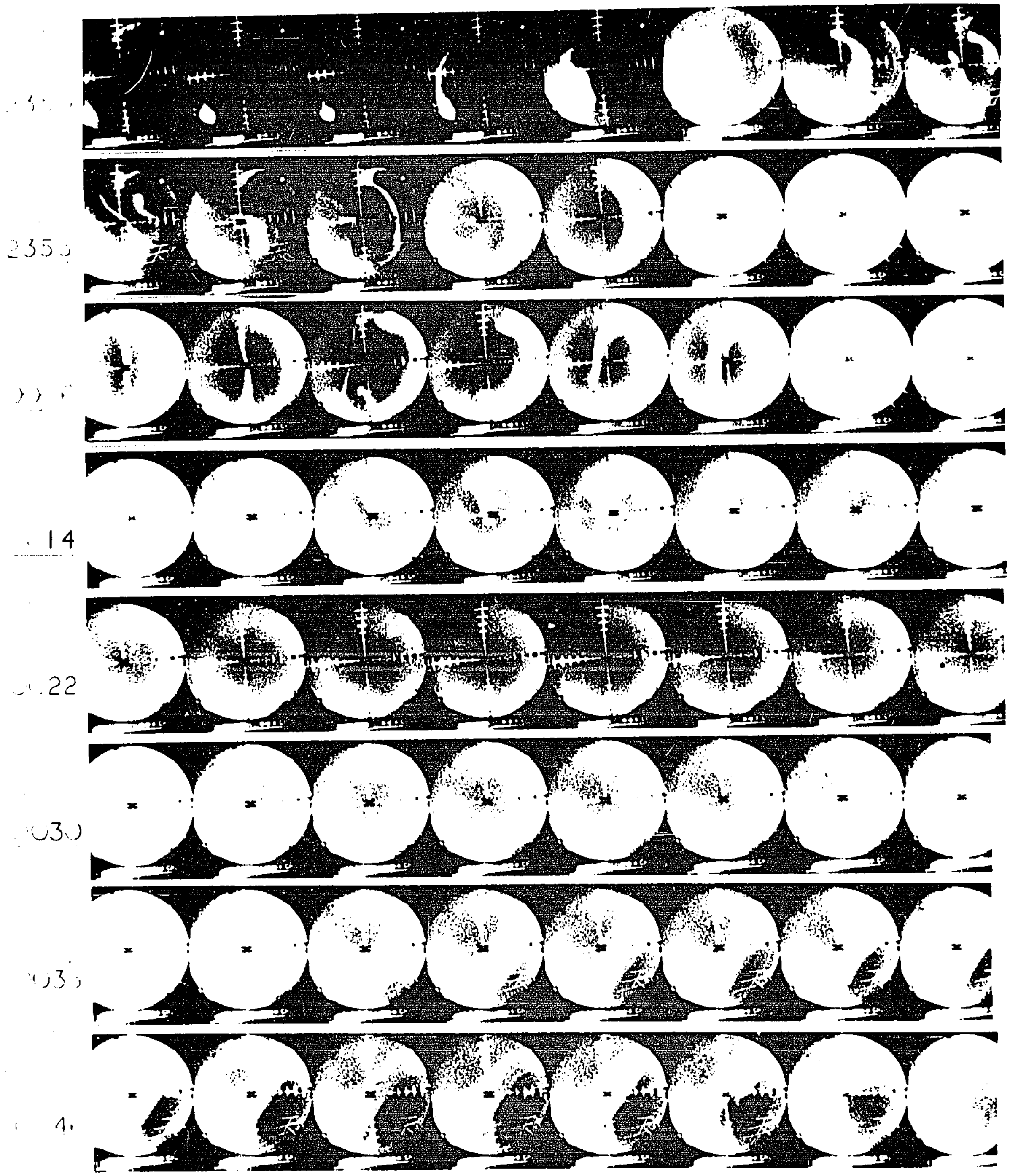
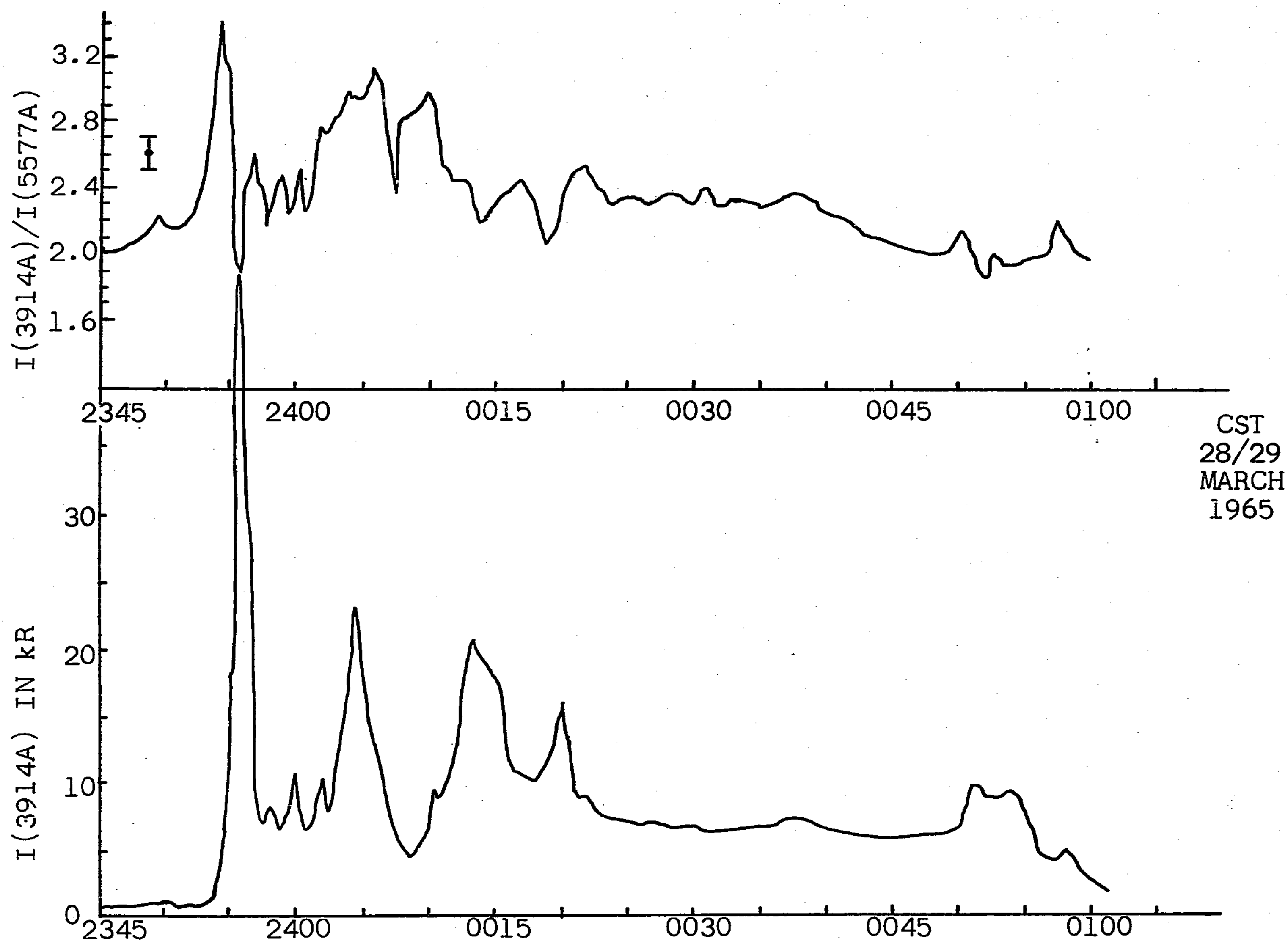


FIGURE 23. ASC PICTURES FOR EVENT E, 28/29 MARCH.



<u>FIGURE 24</u>

INTENSITY AND INTENSITY RATIO DATA FOR EVENT E

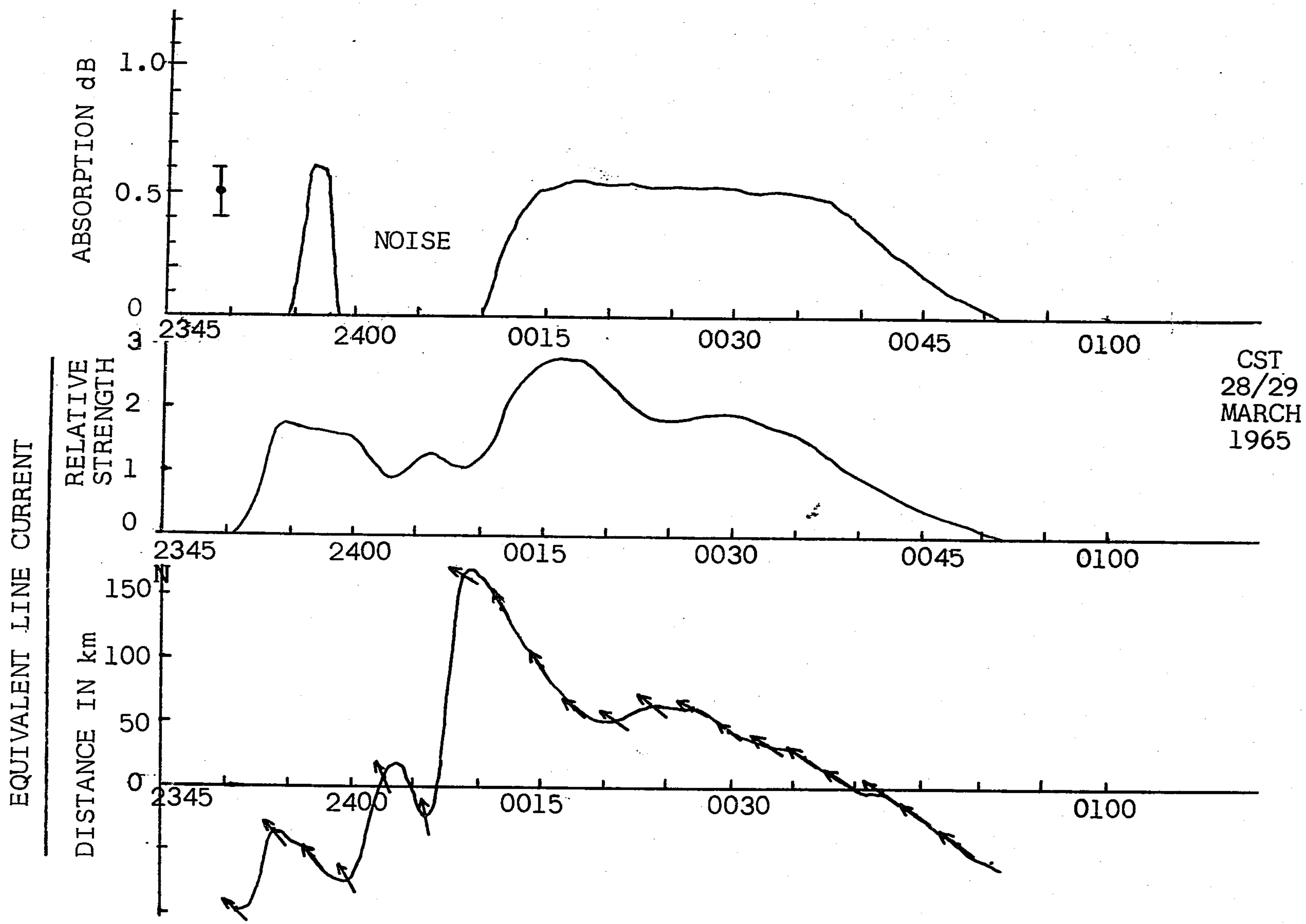


FIGURE 25

MAGNETIC AND RADIO ABSORPTION DATA FOR EVENT E for this view by the riometer records, but scattering greatly reduced the value of the R measurements in this case.

7.5.2 Event E

As far as variations in the 3914A/5577A intensity ratio, R, are concerned, Event E was little different from Event D, as in this case also scattered light was probably responsible for most of the increases observed in R. The main interest of Event E lies in the fact that it contains an example of a very large and short luminosity burst, at 2355-2356, which reached a peak of 50 kR at 3914A (Figure 24).

From 2351 to 2353, ASC pictures show a faint band stretching from the western horizon to the south-eastern horizon and passing through a point at about 30° elevation in the south. At 2354 this band showed signs of brightening and spreading at its western end. This extension of the bright portion overhead presumably caused the luminosity spike on the photometer records at 2355-2356. After that the luminosity in the zenith decreased to a few kR caused by a number of fairly active bands which had all faded out by 2400, except for one at 40° elevation in the north, which had an apparently stationary loop at its eastern end. By 0008 the display had broken up into a confused mixture of bands and patches near the northern horizon.

This mixture of patches and bands degenerated to diffuse aurora with occasional patches by 0015 and lasted until 0030. After 0030 the diffuse aurora seemed to gradually coalesce until by 0100 the aurora had returned to the quiet arc position of 2155, but in this case the band was not quite as well-defined as the original arc had been.

Riometer records for this period (Figure 25) were contaminated by electrical noise, but the bright arc at 2355 was accompanied by 0.6 db in the zenith, and a long plateau of 0.5 db existed between 0010 and 0040, possibly starting earlier than 0010. Magnetometer records (Figure 25) show that the line current was south of Churchill until 0003, although it approached to about 40 km at 2355 when the bright arc occurred. There was only a slight indication of a westward surge at that time. The passage overhead at 0007 seems to have been due to a westward surge, with the current staying north until 0045, when it passed into the south. At 0051 the current passed north again and finally died out around 0200. Estimates of distances are not reliable after 0040 because of the small magnetic deviations.

The association between the arc of 2355 and the passage of a westward surge is not very firm, especially when it is remembered that the auroral activity appeared to develop eastward rather than westward at 2354.

It might be said that this was because the surge originated west of Churchill (this might be possible from one hour before geomagnetic midnight onwards), but if this were so, eastward-drifting patches would have been observed in the later part of the event.(according to the Akasofu model). In fact, stable arcs and bands were observed at this time.

For this event, as for Event C, it seems that the Akasofu model does not explain very sudden outbursts of luminosity as well as it does the more common slower break-ups and more or less coherent expansions of auroral arc systems.

7.6 DISCUSSION OF RESULTS

Clearly, scattered light from forms outside the field of view of the photometers destroyed the usefulness of many of the observations described above. However, in spite of this, some definite conclusions may be drawn.

Firstly, the value of R, the intensity ratio of the 3914A and 5577A emissions measured in the zenith, does not always remain constant, as is shown by the increases in R in Events A and C. In Event A, scattering could not have caused the observed increase in R, since the aurora was diffuse and widespread before and after the increase, and hence the effect of scattering would be constant.

Similarly, in Event C the magnitude of the increase in R (100%) shows that it could not have been due to scattering, since ASC pictures and an outside observer indicated bright aurora in the field of view of the photometers and no very bright forms outside it. For scattering to have caused a 100% increase in R, the auroral intensity everywhere in the sky outside the field of view would have had to be at least an order of magnitude greater than inside. In the case of the apparent increases in R found in Event B, it is impossible to be sure that scattering was not significant, but examination of ASC pictures indicates that interference from scattering was probably small for a few periods when R was rather higher than normal (about 20% higher).

Since increases in R apparently do occur, presumably indicating a change in the electron spectrum above about 25 keV (Section 4.5), the frequency of these changes is of interest. From the present data it is difficult to give a meaningful estimate of this frequency for either large or small changes, particularly the latter. However, it seems possible that large increases in R would be observed during intense Class b displays, or during diffuse glows. Small changes may occur more frequently, but since scattered light is a strong source of contamination, it is suggested that measurements to detect small changes in R should be made on the ground using steerable narrow-angle photometers, or above the atmosphere with balloon-borne photometers. The relation of the changes in R to those in the auroral X-ray spectrum might be quite a simple one, since the changes in R are probably caused by changes in the distribution of electrons with sufficient energy to cause X-rays detectable at balloon altitude.

A tentative explanation of the ratio changes observed in the events is that a region of hard electron spectrum is associated with the line-current, while the visual northern border of the aurora is associated with a region of soft electron spectrum. If these two regions are close together (less than about 50 km) large changes might be observed in the individual emission intensities at 5577A and 3914A, with perhaps no large changes in the intensity ratio. If, however, the two regions are separated by about 100 km or more, large increases in R might be expected as the line current approached a station while the visual northern border moved away. This is essentially the same mechanism as that proposed by Clark and Anger (1966) to explain their X-ray results.

The explanation fits fairly well with the results of Event A, and possibly with those also of Event B. The time scale of the change in R in Event A is consistent with that required for auroral arcs to move about 100 km at a speed of 1-2 km/sec, which is a typical north-south speed for an arc (McEwan and Montalbetti, 1958).

The suggested mechanism, which is based on the Akasofu model, does not however appear to explain the large increase in R in Event C. Event C was preceded by an eastward motion of the visible auroral disturbance while later a westward movement was observed. On the Akasofu model, the order of these movements would be expected to be reversed. The sudden increase of auroral activity in Event C and that observed in Event E, do not seem to be explained very well by the model. The model indicates that one should expect the auroral activity to 'spread out' from some point near magnetic midnight. Events C and E, on the other hand, began very suddenly as though the increase in auroral activity had a local origin, rather than being a time-delayed effect of a disturbance elsewhere, as in the Akasofu model. However, from Events A and B there seems to be some indication that the mechanism proposed above for the changes in R is probably applicable whenever the Akasofu model is.

Because of the small number of observations, this suggestion must be regarded as mainly speculative, until further measurements of R have been made, over a long period and under circumstances where scattering is negligible. The main importance of the present measurements is that increases in R have been definitely observed at times when spectral hardening is indicated by absorption and visual effects, thus showing that R may be used as an index of the hardness of the electron spectrum, in the same way that absorption/luminosity measurements and auroral X-ray data have been used.

CHAPTER EIGHT

CONCLUSIONS

1) An examination has been made of the relative importances of the two processes usually assumed to be of importance in diminishing the intensity of the auroral green line at low altitudes, namely decreased atomic oxygen concentration and collisional deactivation. This examination has shown that collisional deactivation by atmospheric constituents is probably of minor significance and that the decreasing concentration of atomic oxygen below 95 km is the major cause of the extinction of this emission. It is therefore expected that the intensity ratio I(5577A)/I(3914A) should decrease with decreasing altitude below 95 km, but this decrease would apparently be due to a decrease in the abundance of atomic oxygen, rather than to collisional deactivation. Evans and Vallance Jones (1965) concluded that their observed decreases in the ratio I(5577A)/I(3914A) could be accounted for by collisional deactivation of the OI ^1S state. However, in reaching this conclusion they took no account of the apparent large increase in the rate of excitation of the ^1S state towards lower altitudes, reported by Omholt (1955). This large increase is contrary to one of the initial assumptions of the analysis by which it is inferred, and the conclusions of the analysis are thus in doubt.

2) From a study of colour vision theory for low light levels, it is concluded that the intensity ratio I(5577A)/ I(N_2 1PG) must decrease at altitudes typical of the red lower borders of Class b displays, presumably because of collisional deactivation and decreased atomic oxygen abundance, and probably also by enhancement of the N_2 1PG intensity through the Thompson-Williams process. This implies that the experimentally determined luminosity-height profiles usually given for the emissions $[OI]_{32}$, N_2 1PG, and N_2^+ 1NG, which show them coinciding at low altitudes, must be in error. This error may be due to insufficient height-resolution of the measurements. It is suggested that profile measurements using rocket-borne photometers are required to obtain experimental confirmation of these views.

As a further consequence of the colour sensitivity of the eye at low light levels, it was concluded that Class b displays can arise from a Class IBC II aurora in three ways:

a) A simple overall electron flux increase by a factor of 10 (to give an IBC III or III+ aurora), with no electron spectral change, could cause the Class c display to brighten sufficiently to show red on the lower edge, provided the initial incident electron spectrum contained significant numbers of electrons of about 100 keV which could penetrate to the height of about 80-85 km at which the red lower border occurs.

b) A hardening of the electron spectrum could result in sufficient enhancement (by a factor of 10) of the lower red emissions relative to the higher green line, so giving a Class b display.

c) Both processes (a) and (b) could occur simultaneously, i.e. combination of spectral hardening and intensity increase could occur. In case (a) a faint red sensation would probably result, while the more brilliant coloured displays are more likely to occur through the operation of process (b), but the dependence of the colour sensations on brightness shows that an increase in the visual red/green ratio does not, ipso facto, imply any change in the actual photon intensity ratios.

3) Observations were made of I(3914A) and I(5577A) and $I(N_2$ 1PG) in the zenith on several nights. The main interest in these stemmed from the changing ratios of the intensities, but some general features of the emissions were noted:

a) With the wide viewing angle used, no intensity increases were observed to give values of the fractional rate of change of the 5577A intensity greater than about 15% per second (e.g. 4kR/sec when I = 25 kR). This seems a lower figure than has been observed by other workers using narrow-angle photometers, and suggests that the reported large values of this quantity occur because of motion into the field of view or only over small areas of the sky.

b) No obvious quasi-periodic fluctuations were observed with periods less than about 2 seconds. This again is possibly because such fluctuations, if present, are either incoherent over the field of view or because they are localized in one part of the sky, and of small amplitude compared to the total signal.

4) Observations were made of changes in the ratio I(3914A)/I(5577A) in the zenith as an indication of hardening of the incident electron spectrum. The usefulness of these observations was greatly diminished by scattered light from auroral forms outside the field of view, which cannot be accurately compensated for without a knowledge of the brightness, extent and position of the extraneous forms. It appears therefore that observation of this ratio as a spectral technique is more suited to balloon operation than to ground operation. Alternatively observations of both the 3914A and the 4709A bands of N_2^+ 1NG could be made to determine the importance of scattering at any time (McEwan, 1965).

For long periods I(3914A)/I(5577A) remained almost constant at around 1.9 to 2.1 with some increases to about 2.5 which may have been caused by scattered light, but on at least two occasions large increases in the ratio were observed when these could not have been due to scattered light. One of these increases (to a value of 4.5) occurred during a brilliant Class b display, and this indicates that the red colour in that case arose mainly through process (b) above. (During this display measurements indicated a value of 0.5 for I(5577A)/I(Total N_2 1PG). Owing to photometer insensitivity no other valid measurements of this ratio could be made.) The other increase (to 3.5) occurred during the post-breakup diffuse glow and in agreement with indications of spectral hardening from absorption/luminosity ratio measurements. This serves as an indication that I(3914A)/(5577A) is indeed an index of the spectral hardness, and that measurements of the ratio made from balloons would be useful in attempting correlations between X-ray flux and auroral luminosity.

5) An attempt was made to provide a morphological explanation for the observed intensity ratio changes. In general the observations were in fair agreement with the modification of the Akasofu model proposed by Clark and Anger (1966), who give results showing that a spatial separation sometimes exists between the regions of high- and low-energy electron precipitation, which appeared to be associated with the line current and the visual auroral northern border respectively. While this model proved useful in outlining the development of the substorm for some displays, it did not seem to apply so well in the

cases of extremely bright and sudden outbursts of aurora, in that the association between these outburst and the westward surges of the model was not very marked.

It is suggested that observations of the ratio I(3914A)/I(5577A), made from balloons simultaneously with auroral X-ray measurements, should be of help in clarifying the electron spectral variations associated with auroral substorms. Such observations, which presently are mainly qualitative in nature, could be put on a more quantitative basis when further data becomes available on emission intensity profiles and atmospheric composition at auroral altitudes and latitudes.

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TABLE 2 - Visibility of aurora with I(5577A) = 400 kR and I(N_2 1PG) = 2000 kR

Designation	Wavelength Angstroms	Intensity I kR	Energy $h\nu$ eV	P(= I x $h\nu$) x 10^{10} eV/cm^2(col.)sec	PX	PY	PZ
					(X,Y,Z are the ICI distribution coefficients) Units as for P		
N_2 1PG bands in order of visual importance							
(7,3)	5985	16	2.1	3.36	3.56	2.18	0.003
(6,2)	6039	16	2.06	3.32	3.5	1.93	0.003
(12,7)	5352	6.5	2.33	1.51	0.341	1.38	0.045
(8,4)	5931	8.5	2.11	1.79	1.87	1.28	0.002
(11,7)	5779	6.5	2.16	1.4	1.23	1.25	0.003
(9,5)	5879	6.8	2.13	1.45	1.17	1.17	0.001
(10,6)	5829	5.8	2.4	1.39	1.32	1.17	0.001
(5,1)	6089	10.5	2.04	2.14	2.14	1.08	0
(6,3)	6583	79	1.90	15.0	2.86	1.06	0
(7,4)	6505	47	1.92	9.0	2.54	0.96	0
(5,2)	6661	88	1.88	16.6	1.98	0.71	0
(8,5)	6432	14.2	1.95	2.77	1.12	0.432	0
(4,1)	6741	86.6	1.86	16.1	1.09	0.42	0
(11,6)	5390	1.6	2.32	0.372	0.103	0.352	0.082
(9,6)	6360	7.5	2.23	1.68	0.875	0.336	0
(Other bands in the N_2 1PG system are so weak or so far in the infrared as to be invisible)							
Total for the first ten bands given above (see text)					20.5	13.5	0.06
'Equivalent N_2 1PG'	5950	92	2.1	19.3	20.4	13.4	0.02
$[OI]_{32}$	5577	400	2.25	90.0	50.0	90.0	0.43
Total for 400 kR of $[OI]_{32}$ plus 2000 kR of N_2 1PG					70.5	103.5	0.5
'Equivalent Aurora'	5650	480	2.2	106.0	72.0	104.0	0.3

APPENDIX

CALLIBRATION ON COLOURS IN AURORA

This calculation is concerned mainly with the colours observed in a Class b display, in which the two dominant features are the green (5577A) emission and the red (N_2 1PG) emissions. Broadfoot and Hunten (1964) indicate that an aurora of IBC III, or I(5577A) = 100 kR, has a total N_2 1PG intensity of about 500 kR, rather than 2000 kR as given by Chamberlain (1961, p.197). The figure of 500 kR will be used as the basis for this calculation, since the results of Chapter Seven indicate that it is probably more accurate. To ensure that several of the bands of the N_2 1PG system can be regarded as being above the colour threshold of the eye, the auroral display considered will be assumed to have an N_2 1PG intensity of 2000 kR and a 5577A intensity of 400 kR.

Table 2 gives the wavelengths of the band-centres (Turner and Nicholls, 1954) of the fifteen visually most important N_2 1PG bands, arranged in order of visual importance. The band-centre is the wavelength half-way between the wavelengths at which the band intensity has fallen to 50% of its peak intensity. The photon intensities of each band were calculated using the values of the relative photon intensities and of the upper level populations as given by Broadfoot (1963) and Broadfoot and

Hunten (1964).

The distorted colour vision threshold of the normal eye was assumed to be about 10^{-6} lumens/cm^2, after Roach and Jamnick (1958) or Figure 3. This is equivalent to 1.5×10^{-2} ergs/cm^2 sec at 5500A or to 2.2×10^{-2} ergs/cm^2sec at 5985A, which is the wavelength of the (7,3) band, visually the strongest in the N_2 1PG system. Table 2 gives the intensity of this band as 16 kR (if the total N_2 1PG intensity is 2000 kR), and the energy of the emission as 2.1 eV, or 3.35×10^{-12} ergs, per photon.

Thus the power radiated in the aurora (considered as a thin sheet) by the (7,3) band is given by

$$16 \times 10^9 \times 3.35 \times 10^{-12} \text{ ergs/cm}^2 \text{ sec}$$
$$\doteq 5.4 \times 10^{-2} \text{ ergs/cm}^2 \text{ sec.}$$

According to our assumptions this figure is about a factor of 2.5 above that required for colour perception so this band should be visible as a faint red (if isolated from other colours). The second last column (P x Y) in the table gives the relative importance of the visible bands for colour vision, taking into account wavelength and intensity, so we see that there is a good chance of the first ten bands given being seen and contributing to the red colour. However a decrease in intensity by a factor of 2 would not merely reduce the intensity of all the bands by a factor of 2 but would also reduce the number of bands contributing to the colour sensation, as all the bands except (7,3) and (6,2) would no longer be above the colour threshold and hence would become invisible. Or in other words, a decrease by a factor of 2 in intensity has led to a decrease in brightness of more than 6. The figure 6 is arrived at by comparing the sum of the relative visual importances for the first ten bands with half the sum of the relative visual importances of the bands (7,3) and (6,2).

The above is merely a restatement of the fact that the visibility of red relative to that of green falls off rapidly with decreasing intensity (the Purkinje effect, Section 5.2.3), but its main importance lies in the fact that this process occurs for the N_2 1PG system in auroras of about IBC III or III+. In actual practice the observed effect will not be as clear-cut as we have calculated it. The colour threshold used is not a sharp one, nor is it a constant threshold from one observer to another. The transition will be further diffused by the effects of angle of view and the part of the retina being used -- this might correspond to cases when observers report they think they can see colour but are not completely sure about it. There is also the fact that some doubt exists over the total intensity of the N_2 1PG system in an IBC III aurora, perhaps because various observations may have been made on auroras excited by electrons having considerably different energy spectra.

None of these factors, however, is important enough to put the colour-colourless transition outside the possible range of auroral intensities, and it seems probable that the change does in fact occur at brightnesses not infrequently observed in auroral displays. This means then that a red colour is to be expected if the aurora brightens enough. If however the red emission is distributed in the same way as the green 5577A emission throughout the height of the aurora, the combination of the two colours can lead only to a yellowish-green effect. This can be seen by taking the X, Y, and Z coefficients for the 5577A line and the bands 1-10 of the N_2 1PG system, weighting them according to intensity, and summing the X values, the Y values, and the Z values, and then from Figure 2 finding which spectral or other colour is closest to the resultant. This is given in Table 2 as 5650A, which would appear yellow-green. A bright aurora in this case would then appear as a homogeneous yellow-green display, not one having red and green sections.

The colour threshold at 4700A [the (0,2) band of the N_2^+ 1NG system] is 1.55×10^{-1} ergs/cm^2 sec. A photon of this wavelength has an energy of 2.65 eV, therefore an intensity of 1 kR of this emission represents a radiated power of

$$2.65 \times 1.6 \times 10^{-12} \times 10^{9} \text{ ergs/cm}^2 \text{ sec}$$
$$= 4.3 \times 10^{-3} \text{ ergs/cm}^2 \text{ sec.}$$

This indicates that an intensity of about 28 kR is required before this emission rises over the colour threshold. The results of Petrie and Small (1953) indicate that this corresponds to an intensity of 470 kR at 3914A and 140 kR at 4278A [the (0,0) and (0,1) bands of N_2 1NG, respectively]. Because of their much lower visibility coefficients, the latter emissions would certainly not be visible at this intensity, which corresponds to an IBC III+ aurora. The 4709A band is apparently the only N_2 1NG band capable of causing a blue colour in a normal aurora of this brightness, and could affect the colour appreciably only on the lower border, where the green line would not overwhelm it. Its effect on the red lower border would be to cause a slight purple colour; such an effect can often be observed for Class b displays near the zenith (Evans and Vallance Jones, 1965). The fact that this purple colour can be observed in some Class b auroras which do not seem very bright indicates that the ratio $I(N_2\ 1NG)/I(5577A)$ is probably rather larger in these auroras than has been assumed in the calculation above. This of course agrees with the large increase in this ratio found in Event C.