Scientific Results of the South African Antarctic Ionosphere Programme 1962-1970

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1. Introduction

At the end of 1960 the Department of Physics of Rhodes University was invited to participate in a scientific research programme which was envisaged for the third South African National Antarctic Expedition, with its base at Sanae, 70°18′S, 2°21′W. The Department proposed an ionosphere research programme which was approved by the authorities. During 1961, arrangements were made to borrow a Cossor Portable Ionosonde from the National Institute for Telecommunications Research of the Council for Scientific and Industrial Research. This instrument had previously been operated at Marion Island during the International Geophysical Year. The N.I.T.R. also offered on loan a pulse transmitter and receiver, operating at 10,74 MHz, which had been used for oblique-incidence transmissions between Johannesburg and Salisbury, Rhodesia.

After his appointment in October 1961 as a member of the expedition (SANAE 3), D.C. Baker reconditioned the instruments at the N.I.T.R. and took them to Antarctica on board the new research vessel *RSA* in December of that year. The members of SANAE 3 were occupied in the construction of the new base buildings after they arrived in Antarctica, but Baker was ready to test out the ionosonde by the middle of May 1962. He also made the first oblique-incidence pulse transmission to Grahamstown before the end of that month; this was successfully received and recorded at Rhodes at the first attempt. Four years of data have been recorded, but their interpretation has proved to be very difficult and no further work has been done on them. From 5 June 1962 onwards values of the ionospheric parameters f_0F2, f_0F1, f_0E, f_0Es, f_BEs, f_{min}, h′F2, h′F1, h′E and h′Es, scaled from the ionograms at Sanae, have been transmitted in a pre-arranged code by radio to South Africa, edited at Rhodes University and doubtful values checked by radio-telephone, and issued as the "Monthly Bulletin of Ionospheric Characteristics at SANAE, Antarctica".

In the following year the programme was placed on a sounder, five-year financial basis through the Department of Transport, and the appointment of a research assistant, and after some years also of a permanent Antarctic Research Officer at Rhodes, became possible. The present arrangement is for the ionospheric physicist to be appointed on the 1st April, after which he is trained in ionosonde operation and maintenance and in the interpretation of ionograms, until he joins the other members of the expedition in November. After serving for a year in Antarctica, he returns to Rhodes for a further year, which is spent on checking the bulletins for the year and interpreting the results; this may lead to a Master's or Doctor's degree. The ionospheric physicists who have served with the various expeditions during the period under review are:

1962	SANAE 3	D.C. Baker, B.Sc. (Hons.) (Rhodes)
1963	SANAE 4	D.G. Torr, B.Sc. (Hons.) (Rhodes)
1964	SANAE 5	M.B. Ezekowitz, B.Sc. (Hons.) (Rhodes)
1965	SANAE 6	D.W. Sharwood, B.Sc. (Hons.) (Rhodes)
1966	SANAE 7	D.P. Homann, B.Sc. (Hons.) (Rhodes)
1967	SANAE 8	A.W.V. Poole, B.Sc. (Hons.) (Rhodes)
1968	SANAE 9	M.H. Williams, B.Sc. (Hons.) (Rhodes)
1969	SANAE 10	S. Engelbrecht, B.Sc. (Stell.)
1970	SANAE 11	D.W.L. Scorgie, M.Sc. (Natal)

2. The Ionosphere at Sanae

The E and F1 regions of the ionosphere at Sanae do not show any obviously unusual features, though there are reasons to believe that a more careful study may be very rewarding, as will appear later in this paper. The F2 region, on the other hand, was very soon found to exhibit some unusual features.

The first of these to be reported (*Baker and Gledhill*, 1964) was that the daily maximum of f_0F2, which normally occurs nearly at local noon at most stations, was reached at 06 local time at Sanae during the summer months November-February. (It should be noted that, on account of its longitude, local time at Sanae is almost exactly the same as UT.)

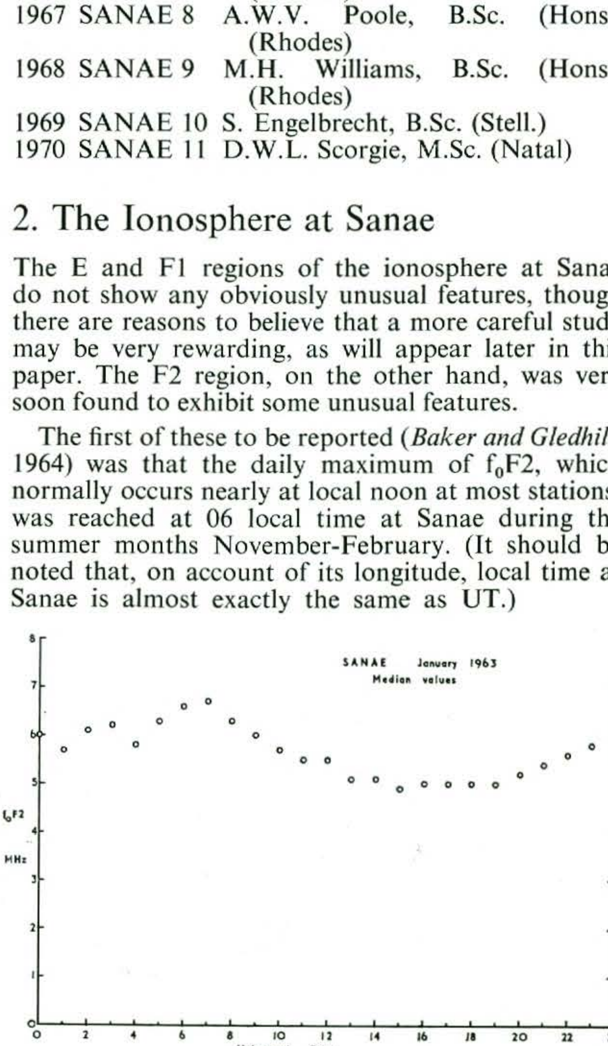

Fig. 1. Median values of f_0F2 for January 1963 at Sanae.

As an example, Fig. 1 shows the mean values of f_0F2 for January, 1963. This type of anomalous behaviour was first noted at Port Lockroy, in the Antarctic Peninsula, by *Coroniti and Penndorf* (1959), and shown to exist in some degree or other at several other Antarctic stations by *Hill* (1960). Sanae was thus found to belong to the small group of stations which lie in the vicinity of the Weddell Sea, and the phenomenon also occurs to a small extent at some stations in the northern hemisphere. Considerable effort has been expended by various workers in trying to explain this puzzling phenomenon (*Rastogi*, 1960; *Hill*, 1960; *Duncan*, 1962; *Piggott and Shapley*, 1962; *King et al.*, 1968; *Sato* 1968; *Torr and Torr*, 1969a; *Duncan*, 1969; *Pike*, 1970). Thermal expansion of the atmosphere, temperature variation of the ionospheric reaction rate coefficients, the effects of winds blowing the ionospheric plasma across the geomagnetic field lines, ionization by precipitated charged particles from space and other causes have been put forward, but there is as yet no generally accepted explanation of this phenomenon.

The other notably unusual feature of the F2 region at Sanae is its variability. Large deviations of the critical frequency f_0F2 and the virtual height h'F2 from their median values are more frequent at Sanae than at any other station studied in the vicinity of $L=4$ (*Gledhill, Torr and Torr*, 1967). Since this aspect of ionospheric behaviour at Sanae is believed to be closely linked with particle precipitation, it is discussed further in section 5 of this paper.

3. The South Atlantic Geomagnetic Anomaly

The earth's magnetic field is not of uniform strength on the surface of the planet at all points having the same dip angle, as it would be if it were the field of a dipole situated at the centre of the earth. As Fig. 2 shows, there is a large area in the vicinity of Rio de Janeiro where the total intensity at the surface shows very low values, compared with those at other places. As a result, the best-fitting dipole is displaced from the centre of the earth 342 km towards a point in the Western Pacific Ocean. Even with this displacement, deviations of the observed field from the dipole field are considerable (*Chapman and Bartels*, 1940), and in the South Atlantic Region are very large and negative. This region is therefore referred to as the South Atlantic Geomagnetic Anomaly.

Particles such as electrons and protons, trapped in the magnetosphere, will therefore approach the earth's surface more closely in this region than in any other, before reaching the value of the magnetic intensity required to reflect them back again, i.e. their mirror points will be very low in the region of the anomaly (Fig. 3). *Dessler* (1959) appears to have been the first to point out that in this way the mirror points of many particles would fall so low that the particles would be lost from the radiation belt by interactions with the molecules of neutral gas in the upper atmosphere. Almost at the same time, the Argus experiment (*Christofilos*, 1959) was performed, in which three nuclear bombs were exploded at heights of about 500 km in the vicinity of Tristan da Cunha. The drift of the electrons from these bombs was observed by several means, and the loss processes were discussed by *Welch and Whittaker* (1959), who concluded that most of the Argus electrons were lost by interaction with the atmosphere over the ocean west of Cape Town.

Experimental observations of large fluxes of high-energy electrons at F-region heights in the anomaly were first reported by Ginzburg and his group in the U.S.S.R. (*Kurnosova et al.*, 1962; *Ginzburg et al.*, 1962). Two "cosmic ships" recorded isotropic fluxes of more than 100 electrons $cm^{-2}\,s^{-1}$ of energy greater than 8 MeV (though it is probable that the counters were in fact responding to bremsstrahlung from much larger fluxes of lower-energy electrons). Fig. 4 is a reproduction of Fig. 4 of *Ginzburg et al.*, (1962), showing the enhancement of electron flux by a factor of about 100 in two regions. The one centred about 30°W, 30°S is referred to by the Russian groups as the South Atlantic Anomaly and that centred about 0°E, 63°S, just to the north of Sanae, as the Southern Anomaly. The satellite was at a height of 330-340 km when it passed through these anomalous regions on 19/20 August, 1960. Observations of electrons with energies greater than 1 MeV at heights of about 400 km during September 1961, showing fluxes in the anomaly enhanced by factors of

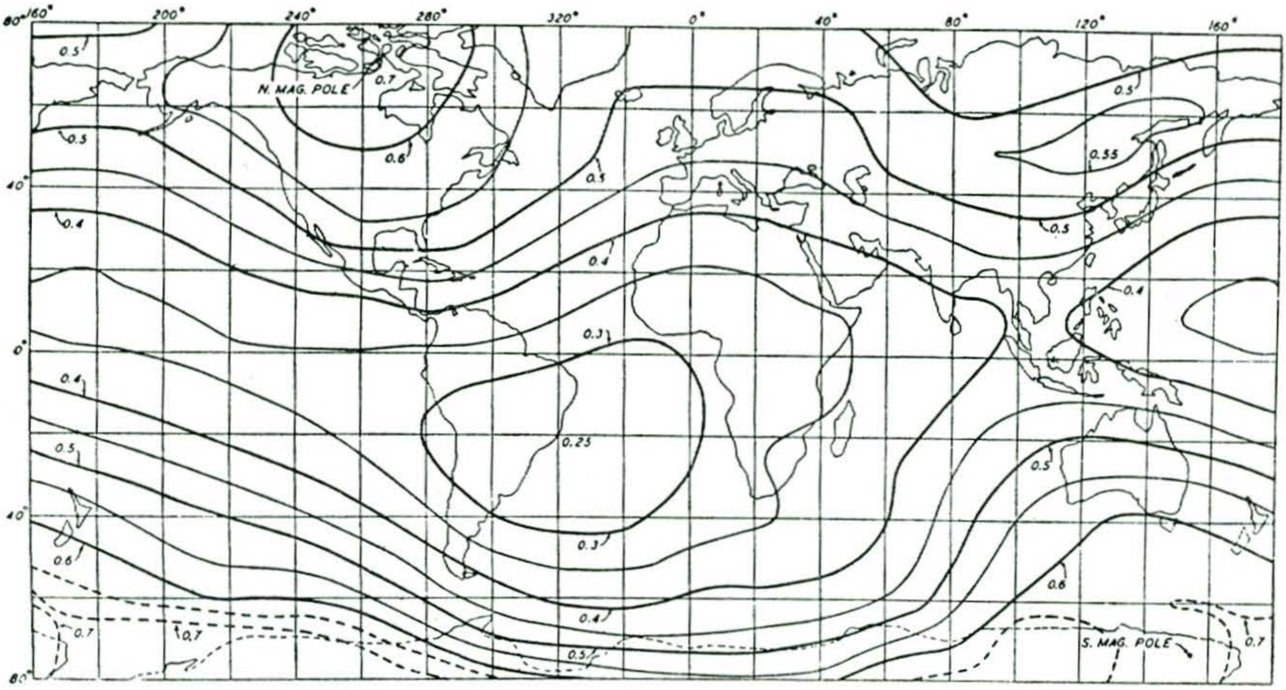

Fig. 2. Lines of equal total intensity (F) for 1922. (Drawn by Ennis from data scaled by Dyson and Turner from British Admiralty Charts) — from Chapman and Bartels (*1940*).

100 and more, were also published later by *Seward and Kornblum* (1963).

It thus became evident that Sanae was in a most favourable position to study the effects on the upper atmosphere of particle precipitation from the radiation belts. Of course, it has been realized for many years that the aurorae are caused by the interaction of charged particles with the upper atmospheric gases. It might thus be expected that effects similar to those observed in the auroral zones would occur in a restricted area somewhat to the north of Sanae.

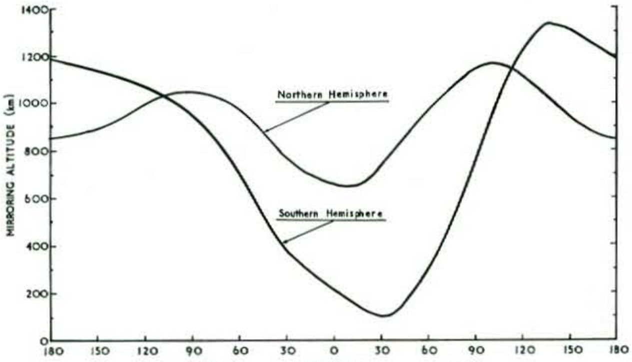

Fig. 3. Mirror point heights for electrons mirroring at 1000 km over Iowa City (from Gledhill and Van Rooyen, *1962*)

4. Effects of the Precipitation of Charged Particles in the Region of the South Atlantic Geomagnetic Anomaly

Chamberlain (1961) has discussed the theory of the penetration of protons and electrons into the upper atmosphere, with particular reference to the auroral zones. It is evident from his treatment that the high-energy electrons observed by the satellites mentioned in section 3 would penetrate well below the 100 km level before giving up much of their energy to the molecules in the atmosphere. Most of the ionization produced by 1 MeV electrons, for example, would lie in the lower D region below 70 km. The main observable effects of this would be increased absorption of radio waves passing through the region, and thus an increase in the notoriously unreliable parameter f_{min} scaled from the ionograms; and the production of X-ray bremsstrahlung which should be observable at balloon heights. *Cladis and Dessler* (1961) first suggested that it would be worth while to look for such X-rays in the anomaly.

Observable effects in the E and F regions would be produced by electrons of much lower energies, in the region of the energy spectrum below 20 keV. It was fortunate, therefore, that the group at the State University of Iowa flew on their satellite Injun 1 Geiger counters which responded to electrons with energies above 40 keV and CdS total energy detectors responding to electrons above 1 keV (*O'Brien et al.*, 1962). They measured pitch angle distributions and

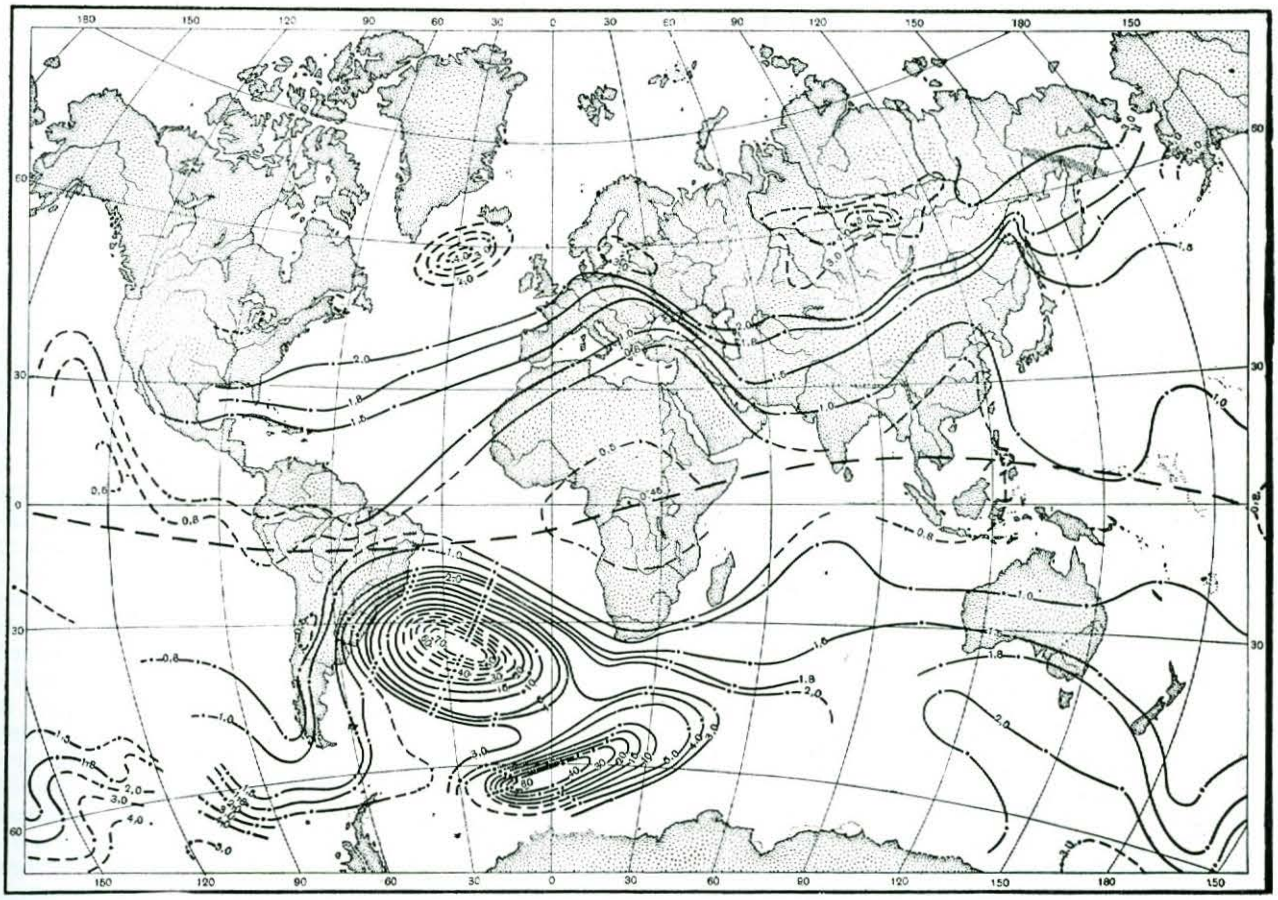

Fig. 4. Counting rates of high-energy electrons reported by Ginzburg et al (*1962*). (*Reproduced from* Planetary and Space Science.)

observed the precipitation of electrons even in the vicinity of Iowa City (*O'Brien*, 1962a, b). Observations were limited to a height of 1 000 km and to the North American area, but *Gledhill and van Rooyen* (1962) pointed out that the L value at which these observations were made was very close to 4, so that the electrons observed by O'Brien would drift into the Sanae region shortly after they were observed. They used the Injun 1 measurements to estimate the energy input to a 1 cm² column of atmosphere above Sanae due to a typical flux of electrons in the range 1-40 keV, and concluded that it may well be of the order of 2×10^{-7} watts. They proceeded to show that this order of magnitude of energy input would be expected to produce observable effects of several different types (*Gledhill and van Rooyen*, 1963).

(*a*) an observable, perhaps even visible, airglow emission, especially at 3914 Å;

(*b*) an intensity of X-rays readily observable at balloon heights;

(*c*) an increase in E-region ionization readily detectable by standard ionosondes, especially at night;

(*d*) heating of the atmosphere, especially in the F region, probably enough to produce observable effects due to the expansion and changes in the reaction rates.

We proceed to discuss the results of later investigation of these predictions.

(*a*) Airglow observations were commenced at Sanae in 1964 by a group under Prof. P. B. Zeeman of the University of Stellenbosch. Instrumental difficulties were encountered in the initial stages of the project, but some data are now appearing (e.g. *Zeeman and Hamm*, 1967). To the author's knowledge, no detailed examination of the results has been made as yet, but preliminary analysis has been disappointing. The observed intensity at 3914 Å appears to be much lower than that predicted by *Gledhill and van Rooyen* (1963). The observations have been used in several studies, e.g. by *Torr and Torr* (1970) to estimate the electron flux precipitating at Sanae and by *Torr and Torr* (1969) in a study of pre-dawn enhancement of airglow.

In view of the position of the main part of the particle concentration observed by *Ginzburg et al.* (1961), between Bouvet Island and Sanae (Fig. 4), airglow photometers have been flown by the Stellenbosch group in aircraft of the South African Air Force on flights to the south of Bouvet (*van der Walt et al.*, 1966). No significant increase in airglow intensity was found at 3914 Å, but an unexpected flux of gamma rays in the range 0,1–1,7 MeV was observed, coinciding with an increase of intensity of the 5577 Å airglow line, in the vicinity of L = 3. Several later flights have been made, and appear to show that there is a significant increase in radiation as far as 60°S in the vicinity of Bouvet Island.

(*b*) No observations of X-rays have been reported, to the best of the author's knowledge.

(*c*) The E-layer has proved difficult to observe reliably at Sanae, owing partly to antenna problems, partly to limited power output available from the ionosonde at low frequencies and partly to the unusually high absorption in the D-region there. An analysis of suitable cases is now under way at Rhodes University but no results are at present available.

(*d*) The analysis of the F-region at Sanae has yielded the most convincing results of the programme so far, and therefore forms the subject of the next section of this paper.

5. The F-Region at Sanae and Electron Precipitation

One of the main problems in investigating the effects of particle precipitation on the ionosphere is to get satellite observations of precipitated fluxes overhead at the station concerned at the same time as the ionograms were taken. Since a given satellite only passes near a particular station twice per day this is a serious difficulty, which is increased by the absence of tape recorders on many of the early satellites, so that telemetry was only available when the satellite was within range of a ground station equipped to record it. Unfortunately Sanae is out of range of all such stations, at least in so far as the region below a height of 2000 km is concerned. The group at Rhodes University was therefore extremely fortunate when Dr I. McDiarmid, of the National Research Council's Division of Pure Physics in Ottawa, offered to make available to it a large number of observations of precipitated fluxes of electrons, with energies greater than 40 keV, made from the Canadian satellite Alouette I; these data had been recorded at St. Johns, Newfoundland, the "field of view" of which station included the area geomagnetically conjugate to Sanae.

Gledhill and Torr (1966) defined the "conjugate area" to Sanae as the region lying between 290°E and 335°E, between invariant latitudes 58° and 60°, and found that there were 77 occasions on which Alouette I passed through this area, for which data were available. Using an arbitrary precipitated electron flux of $1{,}4 \times 10^4$ cm^{-2} s^{-1} as a dividing level, they separated the measured fluxes on each of these passes of the satellite into "high" or "low". As a criterion for abnormal behaviour of the F-region at Sanae, they used the behaviour of f_{min} and h'F2 on the ten magnetically quiet days of each month to define normal conditions, and specified the F region as "quiet" if it lay within the limits of quiet-day behaviour, otherwise as "disturbed", confining these definitions to a period of one hour on each side of the time at which the electron flux had been measured in the conjugate area by the satellite. The precipitated electron flux turned out to be "high" on 28 of the 77 passes, and on *every one* of these the F-region at Sanae was "disturbed". They showed also that the F-region was similarly disturbed at three other stations lying near L = 4, Campbell Island, Argentine Islands and St. Johns, on each of these 28 occasions, but that the disturbances were on the average much more severe at Sanae, where the mirror points would reach their minimum altitude. It thus appeared to be very probable that these disturbances in the F-region were produced by precipitated electrons. It should be stressed, however, that 40 keV electrons would produce their maximum ionization in the vicinity of 90 km above the earth's surface, and it could therefore not be claimed that the electrons observed by Alouette I were directly responsible for the F-region effects. It was assumed that, when electrons with energies in excess of 40 keV were being precipitated, other electrons of much lower energies accompanied them and produced the F-region disturbances.

With such a promising start, *Gledhill, Torr and Torr* (1967) showed that, by lowering in steps the arbitrary "critical flux" of precipitated electrons in the conjugate area, which divided "high" (H) from "low" (L) fluxes, the 77 passes dealt with earlier could be distributed as shown in Table 1, where D indicates "disturbed" and Q "quiet" F-region conditions, in accordance with the criterion used above. This occurred with a critical conjugate precipitated flux of $8{,}2 \times 10^3$ electrons $cm^{-2}\,s^{-1}$. If this value was lowered even further, some of the 19 events in the LQ square moved over into the HQ square, so that a flux below this value would not *always* correspond to a disturbed F-region.

Gledhill, Torr and Torr (1967) proceeded to show that similar tables could be drawn up for two other stations in the southern hemisphere which lie near the shell L = 4, but in each case a different critical conjugate precipitated electron flux was required to give the maximum number of cases in the HD square consistent with a zero in the HQ square, as shown in Tables 2 and 3.

TABLE 1

	Conjugate precipitated electron flux	
F-region	H	L
D	38	20
Q	0	19

For three northern hemisphere stations, St. Johns (L = 3,5), Ottawa (L = 3,7) and Winnipeg (L = 4,2) they found the critical precipitated electron fluxes (now measured overhead and not at the conjugate point) to be all very close to $2{,}4 \times 10^4$ $cm^{-2}\,s^{-1}$.

TABLE 2

Campbell Island		Conjugate precipitated electron flux	
L = 4,0	F-region	H	L
Critical conjugate precipitated flux $2{,}5 \times 10^4$ $cm^{-2}\,s^{-1}$	D	8	9
	Q	0	21

It is not difficult to understand why the critical precipitated electron fluxes, *measured in the conjugate area*, are lower for Sanae and Halley Bay than for the other four stations. Because Sanae and Halley Bay lie in the anomaly region, with its abnormally low mirror points, many electrons which would be regarded as trapped in other parts of the world will precipitate there. Thus the actual flux of electrons precipitating at Sanae must be considerably larger than that precipitating in the conjugate area, $8{,}2 \times 10^3$ $cm^{-2}\,s^{-1}$. It is possible to use the theory of adiabatic particle motion in a magnetic field to estimate what

TABLE 3

Halley Bay		Conjugate precipitated electron flux	
L = 4,5	F-region	H	L
Critical conjugate precipitated flux $1{,}2 \times 10^4$ $cm^{-2}\,s^{-1}$	D	19	7
	Q	0	10

the true precipitated flux at the southern end of a line of force will be, given that at the northern end. This was carried out by *Gledhill, Torr and Torr* (1967), with the results summarized in Table 4.

The concordance of these figures is remarkable, especially in view of the fact that it is not these electrons themselves, but those in the lower-energy part of the spectrum, which are thought to be responsible for the ionospheric disturbances concerned. The conclusion is almost inescapable that a precipitated flux greater than about $2{,}4 \times 10^4$ electrons $cm^{-2}\,s^{-1}$, of energy above 40 keV, is the minimum required to be accompanied by a disturbance in the F-layer satisfying the criteria laid down earlier.

The problem arises, as to whether *every* ionospheric disturbance of this type can be shown to be due to electron precipitation, even when no satellite is present to measure the precipitated electron flux. Gledhill, Torr and Torr (1967) attempted to answer this question by taking a large number of random two-hour samples of the F-region characteristics at each of the six stations in Table 4, and estimating the percentage of the total time for which the region satisfied the criteria for disturbance. They also prepared a graph of the available precipitated electron flux data from Alouette I, showing the percentage of time for which this flux exceeded any given value. Knowing the

Table 4

Station	Conjugate critical precipitated electron flux	Critical precipitated flux at station itself
Sanae	$8{,}2 \times 10^3$ $cm^{-2}\,s^{-1}$	$2{,}5 \times 10^4$ $cm^{-2}\,s^{-1}$
Halley Bay	$1{,}2 \times 10^4$	$2{,}5 \times 10^4$
Campbell Is.	$2{,}5 \times 10^4$	$2{,}2 \times 10^4$
St. Johns	—	$2{,}5 \times 10^4$
Ottawa	—	$2{,}2 \times 10^4$
Winnipeg	—	$2{,}1 \times 10^4$

critical fluxes from Table 4, it was then possible to find the percentage of the total time for which the precipitated flux exceeded the critical value at each station. If all F-region disturbances of the type studied are produced by precipitated electrons, these percentages should be similar. Table 5 shows that they are astonishingly close, offering further confirmation of the hypothesis.

TABLE 5

Station	% total time for which critical flux exceeded	% total time for which F-region disturbed
SANAE	67	65
Halley Bay	53	58
Campbell Is.	29	31
St. Johns	24	23
Ottawa	28	26
Winnipeg	30	31

It is readily seen that the percentage of time for which the F-region is disturbed at the anomaly stations, Sanae and Halley Bay, is much greater than the average of 28% at the other four stations. This is explained by the greater frequency of precipitation of electrons there, on account of the low mirror points.

There seems to be no obvious reason why these phenomena should be confined to the vicinity of the shell L = 4, and *Torr and Torr* (1967a) have extended the treatment to a total of 17 stations, lying between L = 1,88 and 4,47; of these, five lay in the region of the anomaly, four elsewhere in the southern hemisphere and eight in the northern hemisphere. The average disturbed time at the stations not lying near the anomaly was found to be 28%, all values lying between 17% and 37%, whereas the stations in the anomaly region gave: Argentine Is. (L = 2,5), 58%; Sanae (L = 4,2), 65%; Cape Town (L = 1,9), 56%; Marion Is. (L = 2,8) 45%. *Torr and Torr* (1967) also plotted midnight values of MUF (0) i.e. f_x F2, taken from the CRPL prediction chart for May 1963, against longitude, for southern L shells between 1,5 and 5,0. Fig. 5 is a reproduction of their Fig. 1, and shows that there is a very pronounced longitudinal variation, in spite of the absence of any solar photo-ionization at midnight. It should be noted in particular that the minimum in MUF (0) occurs within a few degrees of the position of the minimum total magnetic intensity on each L shell, i.e. in the middle of the South Atlantic Anomaly. In a later paper (*Torr and Torr*, 1968a), they investigated the fluctuations of f_0F2 as a function of longitude and showed clearly that the maximum variation of this quantity occurs in the anomaly region at all times of day, and that it shows a minimum on the shell L = 3, where the precipitated electron flux also shows a minimum.

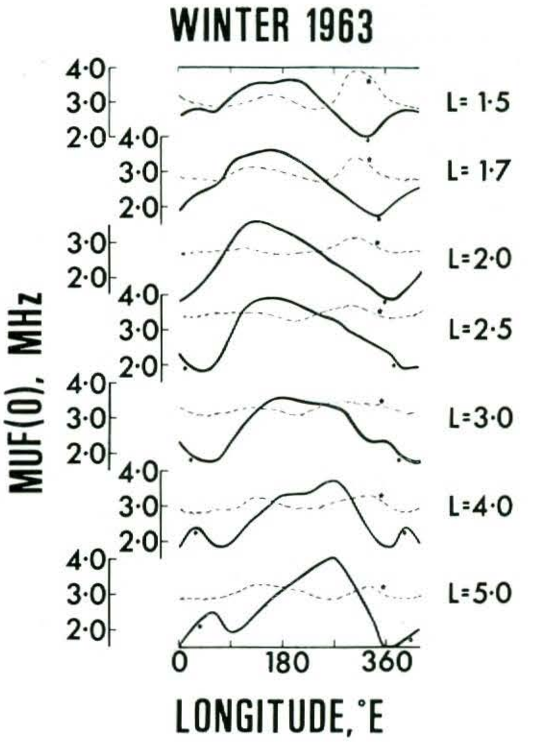

Fig. 5. Longitudinal variation of MUF (O) in the northern (- - - -) and southern (———) hemispheres along various L *shells at local midnight. From* Torr and Torr, *1967a. (By kind permission of The Editor of* Nature).

The above work points very strongly to the conclusions that:

(i) electrons are in fact precipitated from the magnetosphere into the F-region over a large part of the earth's surface;

(ii) the frequency of disturbance of the F-region produced by this precipitation, in the sense that f_{min}, h'F2 or f_0F2 deviates from the quiet-day limits, is about 30% over most of the globe, between L values of 2–5;

(iii) the frequency of precipitation of fluxes of electrons sufficient to produce such disturbances increases towards the centre of the South Atlantic Anomaly, and reaches values in excess of 60% in the middle of the anomalous region.

6. The Nature of the F-Region Disturbances

It has proved to be very difficult to determine the detailed nature of the ionospheric disturbances discussed in the previous section, largely owing to their severity. Of the 28 events originally discovered by *Gledhill and Torr* (1966), 27 showed a blackout on at least one quarter-hourly ionogram and some for more than 24 hours. Nevertheless, at periods when the trace could be seen, it was found that in 27 of the events h'F2 *increased*, by an average of about 100 km, f_{min} was observed to increase by an average of 2 MHz and f_0F2 was usually lower than normal. Detailed analysis of the ionograms is hampered, however, by the increased absorption in the D region produced by the more energetic component of the precipitated electron flux, which makes the trace indistinct and often patchy. By considering one of the less-severe events, *Gledhill* (1970) has shown that there was an increase of electron density at all heights between 100 and 150 km before the blackout occurred, and that this increase could have been produced by a flux of the order of 10^8 cm $^{-2}$ s $^{-1}$ of electrons with an e-folding energy of about 2 keV. Although such values are reasonable, the ionospheric changes involved are so small as to be unconvincing and much further work is required to give reasonably acceptable proof of these ideas.

Torr and Torr (1967b, 1969a) have adopted the alternative approach of solving the ionospheric continuity equations numerically, with realistic expressions for the temperature as a function of height. They have also introduced a production term to take account of the ionization caused by precipitated electrons (*Torr and Torr*, 1968b; 1969b, c), and have shown that such extra production may be very important at most latitudes in accounting for the discrepancy between electron densities calculated on the basis of laboratory-measured rate coefficients and those observed experimentally. One of the main problems in this line of approach is the absence of reliable neutral densities and temperatures in the polar ionosphere.

In a later paper (*Torr and Torr*, 1970) they have shown that the change of rate coefficients with time and temperature together with ionization by precipitated electrons can be made to account very well for the early morning maximum at Sanae.

7. Conclusion

It may appear that the hypothesis, that electrons precipitated from the magnetosphere produce observable effects in the region of the South Atlantic Geomagnetic Anomaly, has been amply substantiated by the work summarized above. However, the evidence is almost entirely circumstantial if subjected to close scrutiny. Thus, the precipitated electrons observed by Alouette I are in the wrong energy range to be responsible for the observed effects, and the conclusions rest on the unproved hypothesis that large fluxes of electrons above 40 keV are always accompanied by even larger fluxes in the range 0,1–10 keV.

Further, the precipitation was observed at the conjugate point, not actually overhead at the ionosphere station concerned. The fluxes calculated in Table 4, while very consistent, do depend on a theoretical conversion from the actually observed conjugate flux to the true overhead flux, and this theory is open to suspicion. It would be far more convincing, as many critics have pointed out, to fire rockets into the ionosphere at Sanae, or indeed anywhere else, during one of these events, with instrumentation to measure the energy spectrum and pitch-angle distribution of the precipitated electrons, thus demonstrating at once that they are there, and that the spectrum and flux is consistent with the observed ionospheric changes. Unfortunately such experiments are likely to be fairly costly, and so far it has not been possible to provide the necessary funds in South Africa.

Alternative approaches are therefore necessary. One which is being tried at Rhodes, at the NITR and at Sanae, is to measure the intensity of the 3914Å and other suitable airglow emissions. The 3914 Å radiation is almost selectively excited by charged particle bombardment at night and is being observed in the hope that it will show increases coinciding with ionospheric events of the type now known to take place simultaneously with the precipitation of particles at the conjugate point. As yet there are no results to report from these investigations. Another avenue is to search out other satellites, instrumented to observe electron fluxes in the low energy region, and try to secure the data from the experimenters concerned. Unfortunately it has proved very difficult even to locate such data, let alone get the experimentalists' permission to use it, but this is being actively pursued by the Rhodes group at present through the World Satellite Data Center at Goddard Space Flight Center, U.S.A. Riometers have been installed at Sanae by the group under Prof. P. H. Stoker at the Potchefstroom University. These should also give some indication of the ionization produced in the D and lower E regions by the more energetic particles, and could be very usefully compared with tape-recorded data from satellites which have observed electron fluxes on the line of force running through Sanae.

The chief need in all this work is for satellite observations of precipitated electron fluxes and spectra in the region of the anomaly. So far as the F-region effects are concerned, which are the only ones reasonably well substantiated thus far, the observations must be made very close to the ionosphere station. Fig. 6 shows bounce and drift times for electrons trapped on the shell L = 4. It will be seen that, while the bounce time does not exceed 7 seconds even for 1 keV electrons, the drift period becomes greater than one day for all energies below 4 keV. It is thus meaningless to refer to such electrons as trapped and drifting round the earth, since they are virtually certain to experience large perturbations before they complete even a frac-

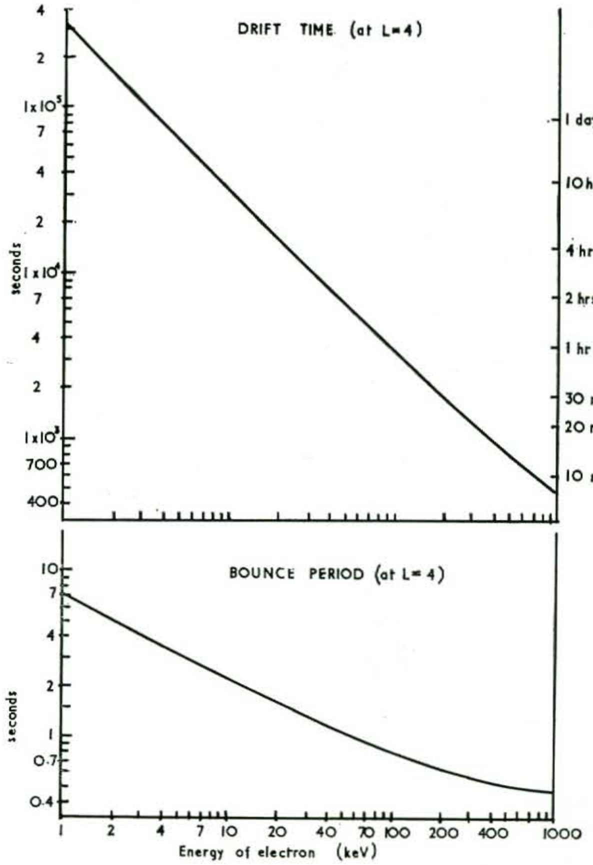

Fig. 6. Drift times (round the earth) and bounce periods for electrons at L = 4.

tion of the total drift. These are the very electrons which deposit most of their energy in the F-region, so that it is imperative to base explanations of such phenomena on satellite data taken very close to the ionosonde, or close to the conjugate point.

Most of the work described in this paper would have been impossible without the financial and logistic support of the Department of Transport and of the CSIR which is gratefully acknowledged.

References

Baker, D. C. and Gledhill, J. A., *The behaviour of the F2 region of the ionosphere over Sanae, Antarctica.* Paper presented at 5th Cospar Symposium, Florence, Italy, May, 1964.

Chamberlain, J. W., *Physics of the Aurora and Airglow*, Academic Press, New York, 1961.

Chapman, S. and Bartels, J., *Geomagnetism*, Vol. 2, Ch. 18, Oxford University Press, 1940.

Christofilos, N. C., The Argus experiment, *J. geophys. Res.*, Vol. 64, 869–875, 1959.

Cladis, J. B. and Dessler, A. J., X-Rays from Van Allen Belt Electrons, *J. geophys. Res.*, 66, 343–350, 1961.

Coroniti, S. C. and Penndorf, R., The Diurnal and Annual Variations of foF2 over the Polar Regions, *J. geophys. Res.*, Vol. 64, 5–18, 1959.

Dessler, A. J., Effect of magnetic anomaly on particle radiation trapped in geomagnetic field, *J. geophys. Res.*, Vol. 64, 713–715, 1959.

Duncan, R. A., Universal-time control of the Arctic and Antarctic F region, *J. geophys. Res.*, Vol 67, 1823–1830, 1962.

Duncan, R. A., Neutral winds and universal-time control of the polar F-region, *J. atmos. terr. Phys.*, Vol. 31, 1003–1009, 1969.

Ginzburg, V. L., Kurnosova, L. V., Logachev, V. I., Razorenov, L. A., Sirotkin, I. A. and Fradkin, M. I. Investigation of charged particle intensity during the flights of the second and third space ships, *Planet. Space Sci.*, Vol. 9, 845–854, 1962. (English translation from *Isskustv. Sput. Zem.* 10, 22, 1961.)

Gledhill, J. A., and van Rooyen, H. O., Cape Town Anomaly and Auroral Emission, *Nature*, Vol. 196, 973–975, 1962.

Gledhill, J. A. and van Rooyen, H. O., The South Atlantic Geomagnetic Anomaly and the radiation belts, *Proc. 5th Internat. Symp. on Space Technol. and Sci.* Tokyo, 1003–1010, 1963.

Gledhill, J. A. and Torr, D. G., Ionospheric effects of precipitated electrons in the South Radiation Anomaly, *Space Res.* Vol VI, 222–229, 1966.

Gledhill, J. A., Torr, D. G. and Torr, M. R., Ionospheric disturbance and electron precipitation from the outer radiation belt, *J. geophys. Res.*, Vol. 72, 209–214, 1967.

Gledhill, J. A., *An ionospheric event apparently due to electrons precipitated from the radiation belt at* $L = 4$. Paper read at IUCSTP Symposium, Leningrad, 1970.

Hill, G. E., Anomalous foF2 variations in the Antarctic, *J. geophys. Res.*, Vol. 65, 2011–2023, 1960.

King, J. W., Kohl, H., Preece, D. M. and Seabrook, C. An explanation of phenomena occurring in the high-latitude ionosphere at certain Universal Times, *J. atmos. terr. Phys.*, Vol. 30, 11–23, 1968.

Kurnosova, L. V., Kolobyanina, T. N., Logachev, V. I., Razorenov, L. A., Sirotkin, I. A., and Fradkin, M. I., Discovery of radiation anomalies above the South Atlantic at heights of 310–340 km, *Planet. Space Sci.*, Vol. 9, 513–516, 1962 (English translation from *Isskustv. Sput. Zem.*, Vol. 8, 90, 1961.)

O'Brien, B. J., Direct observations of dumping of electrons at 1000–Kilometer altitude and high latitudes, *J. geophys. Res.*, Vol. 67, 1227–1233, 1962a.

O'Brien, B. J., Lifetimes of outer-zone electrons and their precipitation into the atmosphere, *J. geophys. Res.*, Vol. 67, 3687–3706, 1962b.

O'Brien, B. J., Laughlin, C. D., Van Allen, J. A. and Frank, L. A., Measurements of the intensity and spectrum of electrons at 1000–Kilometer altitude and high latitudes, *J. geophys. Res.*, Vol. 67, 1209–1225, 1962.

Piggott, W. R. and Shapley, A. H., *Antarctic Research Geophysical Monograph* No. 7, 111 — American Geophysical Union, 1962.

Pike, C. P., Universal time control of the south polar F layer during the I.G.Y., *J. geophys. Res.*, Vol. 75, 4871–4876, 1970.

Rastogi, R. G., Abnormal features of the F2 region of the ionosphere at some southern high-latitude stations, *J. geophys. Res.*, Vol. 65, 585–592, 1960.

Sato, T. Abnormally large electron concentration in the ionospheric F2 region at summer-night in middle latitudes, *J. geophys. Res.*, Vol. 73, 127–142, 1968.

Seward, F. D. and Kornblum, H. N., Jr., Near earth, high latitude satellite measurements of cosmic ray flux in 1961, *University of California report* UCRL — 7633, 1961.

Torr, D. G. and Torr, M. R., Ionospheric effects caused by electrons precipitated from the outer radiation belt, *Nature*, Vol. 216, 1193–1194, 1967a.

Torr, D. G. and Torr, M. R., *An investigation into the effect of temperature changes on the F region electron density distribution in the South Atlantic Geomagnetic Anomaly.* C.S.I.R. Res. Report. No. 263, Pretoria, 1967b.

Torr, M. R. and Torr, D. G., Precipitated electrons as a cause of the irregular behaviour of the F2 region, *Nature*, Vol. 217, 45, 1968a.

Torr, M. R. and Torr, D. G., *A theoretical investigation of the F region of the ionosphere*, C.S.I.R. Res. Report No. 271, Pretoria, 1968b.

Torr, D. G. and Torr, M. R., A method of solution of the F1 layer non-linear ionospheric continuity equation and the early morning and late evening increase in electron density observed at some stations, *Ann. geophys.*, Vol. 25, 571–575, 1969a.

Torr, M. R. and Torr, D. G., The inclusion of a particle source of ionization in the ionospheric continuity equation, *J. atmos. terr. Phys.*, Vol. 31, 611–614, 1969b.

Torr, D. G. and Torr, M. R., Low energy electrons and the ionosphere, *Trans. S. Afr. Inst. Elec. Engrs.*, Vol. 60, 112–117, 1969c.

Torr, M. R. and Torr, D. G., Discussion of letter by Robert T. Bennett, 'Latitude dependence of 6300 A (O I) twilight airglow enhancement', *J. geophys. Res.*, Vol. 74, 5187, 1969d.

Van der Walt, A. J., Stoker, P. H., Mance, J. P., Zeeman, P. B. and Hamm, F. M., Airglow and enhanced penetrating electromagnetic radiation in the Southern Radiation Anomaly, *Space Res.* Vol. VI, 189–202, 1966.

Welch, J. A. and Whittaker, W. A., Theory of geomagnetically trapped electrons from an artificial source, *J. geophys. Res.*, Vol. 64, 909, 1959.

Zeeman, P. B. and Hamm, F. M., *Luggloeddata Sanae Antarktika.* Physics Dept. Report, University of Stellenbosch, 1967.