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The Influence of Geomagnetic Activity on Polar Cap Absorption *

by

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ABSTRACT

In this paper several polar cap absorption events, for which simultaneous riometer data exist for Thule, Greenland, and College, Alaska, are examined in detail in order to make a careful comparison of the ratio of absorption at the two stations. In addition, comparison with other stations both to the south and north of College is made. It is verified that one can divide the polar cap into two regions. In the first, including latitudes to the north of geomagnetic 65° (L = 5.5), the progress of the PCA event is dominated by the time variations of the solar particle flux, and is essentially independent of the geomagnetic field variations. The ratio of absorption College/Thule is usually found to be 0.8 or greater throughout the event.

In the second zone, extending from geomagnetic latitudes of about 64 degrees down to about 55 degrees, the characteristics of the PCA are largely dominated by the influence of the geomagnetic field. It is shown that at L = 4.3, the pre-magnetic storm value of the ratio Farewell/Thule is about 0.14. However, during the magnetic storm, the ratio tends to approach unity. At King Salmon (L = 3.3) it is seldom possible to identify PCA prior to the magnetic storm, although the post-storm value of

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the ratio King Salmon/Thule may approach unity for sufficiently large magnetic storms (maximum $D_{st} > 200\ \gamma$).

The results of this study are compared with satellite studies of the solar particles and with the theoretical calculations of the absorption expected from protons with given exponential rigidity spectra [Webber(1); Bailey(2)]. These results lead to the deduction of an effective cutoff at College of the order of 30 MeV or less, as has been observed directly by satellites in a small number of events.

In the present work, the magnetic activity is characterized by D_{st}. It is found that, in the second zone of PCA activity (the outer ring), the prestorm cutoffs are apparently restored at a greater D_{st} value than that corresponding to onset of the cutoff reduction at the beginning of the storm. The effect may be interpreted in terms of a progressive softening of the proton spectrum as the event progresses.

Author

INTRODUCTION

A study of cosmic noise absorption data from stations well separated in latitude should contribute to an understanding of the effect of the geomagnetic field on the bombarding solar particles, which cause the phenomenon of polar cap absorption.

The present paper extends the catalogs of PCA events by presenting detailed graphs of absorption of cosmic noise for several events not previously discussed in detail in the literature. These events are then examined primarily in terms of the influence of magnetic activity on the flux of particles incident at polar cap and sub-polar cap stations.

The riometer records discussed refer to cosmic noise absorption measured with broad-beamed, vertically-directed, three element Yagi antennas at a frequency of 27.6 Mc/s, located at Thule, Barrow, Ft. Yukon, College, Farewell, and King Salmon (see Table I). The absorption in decibels is given by

$$A\ (\mathrm{db}) = -10 \log_{10} \frac{P}{P_o}$$

where P is the cosmic noise power received, while P_o is the expected noise power under quiet ionospheric conditions at the same sidereal time. This wide beam absorption value which is used in this study may be converted to the vertical, 'line-integral' of absorption by using the detailed polar diagram of the antenna. A fair approximation is that the absorption per unit vertical column is about 70% in magnitude of the wide beam absorption in db. There are also inherent limitations to the accuracy of the wide beam absorption data above about 15 db; for example, a nominal value of about 20 db may be in error by as much as 3 db.

A major problem in interpreting PCA data is the possible coexistence of absorption due to auroral particles. This problem is not important at Thule, but becomes severe for the Alaskan stations located close to the auroral zone. The sudden-onset, short duration auroral events are readily identifiable on the original data. However, the long-duration, slowly varying auroral events are more difficult to separate from the PCA. We have adopted the rule-of-thumb that the PCA contribution is represented by the <u>minimum</u> value of absorption recorded over a several hour period--such a policy is the safest when discussing ratios of absorption as in this paper.

Two other characteristic features of PCA must be recognized in the present study. First, PCA's show strong recoveries during the night hours, a result of increased electron attachment in the absence of sunlight. The nighttime recovery usually sets in at solar zenith angles of 88 to 92 degrees, while the morning increase begins at about 102 degrees. Daytime equilibrium is essentially reached by a zenith angle of about 85 degrees. Whether or not one can make a reasonable interpolation of the PCA across the nighttime recovery depends on several factors, including the inherent rate of change of the solar cosmic ray flux. In general, we have not used the nighttime periods in the comparisons made in this paper. The periods of nighttime recoveries are indicated in the figures by dark underlines.

The second feature is the presence of midday recoveries of absorption during some events at stations close to the outer boundary of the polar cap region. Leinbach(3) has interpreted these recoveries as a local time dependent increase of effective cutoff rigidity of the solar particles near the edge of the polar cap zone. (See also Bailey(2) for a summary of this phenomenon.) If this interpretation is correct, midday recoveries properly belong in the context of this paper; however, we have chosen not to discuss them in detail here.

The graphs accompanying the individual events discussed below contain, beside the PCA data, the D_{st} curves showing the history of the magnetic activity during the period. The times of occurrence of magnetic sudden commencements are also indicated by vertical lines in the figures. For events where D_{st} was not readily available, we have, following the suggestion of Akasofu, derived a rough measure of the same by combining the magnetic data (H component) from the low latitude stations of San Juan and Honolulu. A certain amount of residual diurnal variation is still evident in some of these curves. However, these curves obtained from the two stations certainly give a fair measure of the gross changes in the equatorial ring current. For the July 1959 events we have taken the accurate D_{st} values of Akasofu and Chapman(4). D_{st} is generally considered to be a measure of the ring current. Because the ring current will affect the cutoff rigidities, D_{st} should be a useful parameter in studying the latitude of the PCA boundary. We note, however, that Akasofu and Lin(5) have shown that the ring current alone cannot explain the observed cutoffs for solar protons.

RESULTS

Out of 20 representative PCA events during the period March 23, 1958--October 2, 1961 [Leinbach(3)] only about half have sufficient data for any useful inter-comparison between stations. We have not given detailed comments about the solar flares assumed to have been the source of the protons. Identifications of the most probable flares for each event can be found in the list of Warwick and Haurwitz(6), for example. The important events are described below.

March 23, 1958 (Figure 1)

The polar cap absorption became pronounced only after onset of a weak magnetic storm (1540, March 25; probable associated flare was of importance 3 on eastern limb, 1005 March 23). The ratio College/Ft. Yukon was essentially constant throughout the event, at 0.9 or higher.

VHF scatter data obtained by Bailey(2) [private communication] from very high latitude paths indicate that the flux of particles was relatively small prior to the SC on March 25, and increased markedly thereafter. Thus, in contrast to Webber's(7) conclusion of a reduction in cutoff at College and Ft. Yukon following the SC, we favor the interpretation that the sudden increase of PCA was caused by an increase of flux in the solar beam.

A pronounced daytime recovery was observed at both Ft. Yukon and College on 25 March, during the initial phase of the magnetic storm. Since no riometer data are available from a very high latitude station, no conclusions can be drawn with respect to the probable cutoff energy at College for this event.

<u>April 10, 1958</u> (Figure 2)

No known flare activity was associated with this event, which occurred during an extended period of magnetic quiet. The College/Ft. Yukon ratio was about 0.7 throughout the event. The ratio during the midday recovery was also about 0.7, allowing for the presence of some propagated interference, plus some additional absorption due to a solar flare associated SCNA during the peak of the midday recovery.

<u>July 7, 1958</u> (Figure 3)

This event, associated with a 3^+ flare, followed 31 hours later by a large magnetic storm (SC 0748 UT, July 8; Max K_p reached 9o, Max D_{st} 350 gammas) enables us to compare the absorption within the normal polar cap and the outer ring zone.

The apparent earlier onset of recovery of absorption at College, following the SC, is due to the partial nighttime recovery. The College/Thule ratio was about 0.8 during the recovery phase, and remained constant throughout the main phase of the magnetic storm up to at least 12^h July 10. Afterwards, the ratio apparently decreased. The absorption at Farewell, which was less than 15% of that at College before the SC (0748 July 8, 1958) started rising an hour before SC and reached the College level after the storm began. The absorption is comparable to that at College for the rest of the event. King Salmon, which showed no PCA before the sudden commencement, also recorded strong PCA during the magnetic storm.

Even allowing for the effect of the nighttime recovery, the onset of absorption at King Salmon was retarded compared with Farewell. It is difficult to ascertain when the King Salmon absorption maximized. Correcting for the nighttime recovery, the equivalent daytime value of absorption was probably about 16 db by 12^h UT July 8, well before maximum of the D_{st}. Following the midday recovery on July 8-9, the equivalent daytime absorption at 06^h July 9 was probably still close to that observed at Thule. The absorption at King Salmon decreased to negligible amounts by 00^h July 10, at a time when D_{st} was still greater than 100 γ, and more than 2 db absorption was being observed at Thule.

This event is a clear example of the shift of the lower border of the polar cap region during a magnetic storm, as a result of lowered cutoffs during the storm.

August 16, 1958 (Figure 4)

The PCA data from Thule are incomplete, and missing from College. However, the Barrow registrations show the temporal variations over the polar cap. No significant absorption was seen at King Salmon, even during the magnetic storm. Thus the boundary of the PCA region remained north of 57° geomagnetic, throughout the event.

Farewell showed about 14% of the absorption at Barrow prior to the magnetic storm. There appears to be some evidence that the absorption at Farewell actually decreased slightly while the absorption at Barrow was still increasing. This could have resulted from a relative depletion of particles in the solar beam above the Farewell cutoff.

If the observed day/night ratio of about 4 at Barrow was also applicable at Farewell, the daytime equivalent of the absorption increase observed at the beginning of the magnetic storm should have been about 7 db, close to the interpolated daytime absorption at Barrow. The absorption at Farewell then decreased, until at 14^h August 17 the daytime equivalent value was less than 1.5 db, compared with the corresponding value of about 5 db at Barrow. We cannot be certain what percentage of the absorption at Farewell between 18^h August 17 and 06^h August 18 should be attributed to the solar particles.

Solar cosmic rays were detected on the high latitude passes of the satellite Explorer IV early in the event at 1115 and 1315 August 16 and again on the next passes at 1100 and 1300 August 17, about 4 and 6 hours after the SC, respectively [Rothwell and McIlwain(8)]. The ratio of the counting rates of the unshielded to the shielded Geiger tubes (proton cutoffs of about 30 and 40 MeV, respectively) increased from 1 to almost 3 between the first and second pairs of observations. In view of the mounting evidence that effective cutoffs are very much reduced from the dipole values, it now appears safe to assume that at the latitudes at which these ratios were determined, the geomagnetic cutoff was well below the instrumental cutoffs of the Geiger tubes. Hence the change of ratio was most probably caused by a relative depletion of protons above 40 MeV (equivalent to saying that the spectrum steepened with time). This conclusion is consistent with the slight decrease of absorption noted at Farewell between 14^h August 16 and 02^h August 17.

August 21, 1958 (Figure 5)

This weak event with data missing from Thule and College before the SC (0227 August 22, Max Kp reached 6-) had some unusual features. Barrow showed weak pre-SC absorption and then appreciable post-SC increase, which could be attributed to the arrival of low energy beam following the SC rather than to a change of cutoff. College data showed a 5 minute increase of absorption at the time of SC followed by a large initial phase decrease, before reaching the post-SC maximum of absorption of about 4 db. Unfortunately, the Barrow data for this period were missing due to instrument calibration. The time variations at College could be interpreted as an increase in the cutoff values with initial field compression [Ortner et al.(9)] followed by a recovery of cutoff to the initial or a slightly lowered value during the magnetic storm main phase. Farewell did not register any pre-SC absorption and the post-SC absorption starts about 2 hours after the SC. Thus the lowering in cutoff at Farewell was delayed until the main phase was well underway. The College/Barrow ratio was about unity during the main phase whereas the Farewell/College ratio was 0.5.

August 22, 1958 (Figure 5)

The time of onset of this event (associated flare 3^+, magnetic storm SC at 0140, August 24) could not be determined due to the presence of a solar noise storm. However, the event was clearly in progress by 18^h on August 22 and the pre-SC absorption maximum occurred at about 22^h on August 22. Anderson(10) observed by balloon-borne counters the presence of solar protons of energy > 100 MeV at 1530^h on August 22, with a maximum flux between 1600 and 1900^h, and a continuous decrease thereafter. These particles completely disappeared before the pre-SC maximum of about 8 db was observed at Thule, Barrow, and College at 2200^h on 22 August. Hence the particles responsible for the pre-SC absorption maximum must have had energies < 100 MeV. Rothwell and McIlwain(8) from Explorer IV data deduced a constant ratio of about 3 for the unshielded to shielded counter at 0925 and 1115 on **August** 23. From this as well as Anderson's results, it may be assumed that by that time the spectrum was nearly constant, rich in low energy particles (< 40 MeV) and deficient in protons of energies greater than 100 MeV.

The nighttime recovery during the early part of August 23 at Thule (about 0130 to 0800^h), at Barrow (about 0630 to 1430^h)

and at College (about 0530 to 1430^h) complicate the study of the pre-SC phase of the event. However, from 18^h to 23^h on August 23, both Thule and Barrow reveal an average absorption of about 6 db, whereas College shows about 4 db, giving a College/Thule ratio of 0.7. One might interpret this ratio to mean that the spectrum was very soft at this time. But all the stations register about 6 db just before the SC at 0140^h on 24 August. This leads to the alternate possibility that the midday recovery phenomenon was responsible for the lower value at College during the period 18 to 22^h August 23.

The increase of absorption at Thule following the SC at 0140 August 24 came during a nighttime recovery. Making reasonable correction for the effect of the nighttime recovery, based on the day/night ratio of 1.5 for the previous recovery, the equivalent daytime absorption for the post-SC increase is estimated as 10 db. This increase probably represented an increase of the flux of low energy particles in the solar beam. Barrow data were missing during the first part of the post-SC increase, because of instrument calibration. However, the increase there reached at least 10 db. The post-SC increase was also outstanding at College. In fact, the 20 db absorption recorded at College at about 03^h August 24 is anomalously high compared with the estimated PCA at Thule of 10 db. The explanation for the much greater absorption at College is not clear, although auroral absorption may have been present during this period. By 04^h the absorption had decreased to the polar cap value of about 10 db; throughout the rest of the event, College recorded essentially full polar cap values of absorption.

The distinct change of cutoff at the lower latitudes following the SC can be clearly seen from a comparison of the absorption at Farewell with that at College. Little, if any, PCA was recorded at Farewell prior to the magnetic storm. By 04^h August 24, the absorption at Farewell was nearly equal to that at College, with a ratio Farewell/College of 0.9 or more.

No significant increase of absorption was noted at King Salmon until about 90 minutes after the SC. Even then, the original riometer records indicate that at least part of the absorption was auroral in nature. In any case, the maximum possible PCA recorded at King Salmon could not have exceeded about 6 db, compared with about 10 db at College at the same time. Thus the cutoff reduction at King Salmon was not complete during this event.

Cutoffs were being restored towards normal before 16^h August 24. At that time, King Salmon recorded no PCA, and

Farewell about 1 db maximu, compared with 3 db at College, Barrow, and Thule. An Explorer IV pass at about 1100^h on August 24 shows an increase of 25% in the ratio of unshielded to the shielded counter, compared to the ratio 24 hours earlier (and hence before the SC) [Rothwell and McIlwain(8)]. This indicates a small relative depletion of protons of energy greater than 40 MeV as the event progressed. In many respects, this event seems comparable to a later one on September 28, 1961, where the low energy flux dominated the event except during the initial phase [Bryant et al.(11); Leinbach(3)].

August 26, 1958 (Figure 6)

This event was associated with a flare of importance 3 and a magnetic storm on August 27 with two SC's closely following one another (0243 and 0303^h); K_p reached a maximum of 7-. The Explorer IV data from about 18 hours prior to SC showed the presence of protons down to 40 MeV. The College/Thule ratio at that time was approximately unity and hence it is clear that there was no cutoff greater than 40 MeV operating at College. The Farewell/College ratio changed from about 0.14 before SC to about 0.7 after SC, showing the lowering of the cutoff at Farewell as a consequence of the storm. Pronounced initial phase decreases in absorption occurred at both

College and Farewell [Ortner et al.(9)]. Both of these stations also showed a pronounced midday recovery in absorption on 26 August. No pre-SC absorption was seen at King Salmon, and it is hard to decide whether the small increase observed during the nighttime recovery on the 27th at King Salmon was due to an auroral type of absorption or to PCA. One can see similar increases of absorption at the same time at Farewell and College, but not at Barrow. Hence the increases at the three stations were probably of the auroral zone type. The slight increase in the ratio of the unshielded to shielded counter in Explorer IV, from 18 hours prior to the SC to 5 hours after SC indicates again [Rothwell and McIlwain(8)] a relative depletion of protons greater than 40 MeV as the event progressed.

Marked fluctuations in intensity can be seen clearly at Thule during the initial part of the PCA. A reasonable explanation is a change in the primary proton intensity with time. Other cases, with correspondence in fluctuations between the high latitude stations have also been observed. Similar fluctuations of the primary beam of solar protons have been detected in interplanetary space by Geiger tubes on Mariner IV during the proton event of February 5, 1965 [Van Allen, private communication].

May 11, 1959 (Figure 7)

This unusually long duration event observed at Thule, Barrow, College, and King Salmon was associated with a 3^+ flare, and accompanied by a magnetic storm with SC at 2329 May 11 (max. K_p 8^+). Although no pre-SC absorption was seen at King Salmon, a small increase occurred 3 hours after SC. One may infer that the cutoff was slightly lowered, but nowhere near the polar cap value. An initial phase decrease immediately after the SC is evident in the College data; a less pronounced decrease may also have occurred at Barrow.

Since the College/Thule ratio was close to unity both before and after SC, up to about 18^h May 12, either the changes in cutoff at College during the storm were of no consequence or the minimum particle energy was essentially above the College cutoff. The ratio C/T then slowly decreased, to 0.8 by 06^h May 13, to 0.7 by 12^h May 13, and finally reaching its minimum value of 0.5 at about 18^h May 14. An increase in the ratio, to a maximum value of 0.75 by 18^h May 15, coincided with the onset of the slight increase of D_{st} in the period 12^h May 16 to 00^h May 17.

Thus it is probable that the cutoff was slightly reduced at College during the latter period of increased magnetic activity. The fact that the ratio C/T was again decreasing before the D_{st} maximum at 06^h May 16 may again be due to a continued softening of the proton spectrum with time. This is one of the few events where the College/Thule ratio decreased to a value of 0.5. It is thus necessary to conclude that after 12^h May 13, particles with energy lower than the College cutoff were present in considerable numbers.

The data from King Salmon (L = 3.3) show that the maximum PCA there did not exceed 3 db (at about 04^h, May 12), compared with the concurrent value of 18 db over the polar cap. The Norwegian data [Eriksen et al.(12)] from Trondheim (L = 4.5) indicate that the PCA attained the full polar cap value following the magnetic storm onset. Further south, at Kjeller (L = 3.5), the PCA apparently did not exceed 3 db. However, there is evidence for a midday recovery at Trondheim, which would have also prevented Kjeller from attaining the maximum possible PCA for its latitude. Winckler and Bhavsar(13) reported a sizeable increase of the flux of protons > 100 MeV at Minneapolis (L = 3.3) following the SC. These facts could be interpreted to mean that during the magnetic storm the cutoff at L = 3.3 was reduced, possibly to less than 100 MeV, but not enough to allow the lower energy protons which were giving the greatest fraction of the polar cap absorption.

July 10, 1959 (Figure 8)

This event (associated flares 2^+ and 3^+, magnetic storm SC at 1625 on July 11) is an example of strong polar cap absorption with an associated weak magnetic storm. The dynamic range of the Thule riometer during this period was limited to about 12 db, preventing accurate scaling of the data for absorption in excess of 10 db. The Barrow data, especially for large values of absorption, should also be viewed with caution, due to local interference. The College data show both nighttime and pronounced midday recoveries. King Salmon exhibits only very weak absorption increases, early on the 11th, 12th, and 13t The magnetic storm was very weak, as indicated by the ring current measure D_{st}, which registered only about 25-30 γ maximum [Akasofu and Chapman(4)].

July 14, 1959 (Figure 9)

This event (associated flare of 3^+) is an example of association of strong PCA and an intense magnetic storm. D_{st} reached a maximum value of well over 400 γ following the magnetic storm SC at 0803^h on July 15. The residual polar cap absorption from the previous event still measured over 4 db at College at the time of the onset of this event. King Salmon showed less than a tenth of the absorption at College at 04^h

July 15, before the SC, but reached very nearly the full polar cap value after the SC. It should be pointed out that the gradual restoration of the cutoff at King Salmon corresponded to much higher values of D_{st} than those at the onset of the post-SC absorption. By the early part of the 16th King Salmon showed no absorption at all, while the polar cap value was still about 5 db.

The College/Thule ratio remained almost unity throughout the recovery phase of the event, which implies that the cutoff effects due to the changing ring current were unimportant at College, relative to spectral and flux variations.

July 16, 1959 (Figure 10)

The July 16, 1959 event, with an associated flare at 3^+ and a magnetic storm with SC at 1638^h on July 17, was the last of this series of three events. King Salmon registered only one tenth of the absorption at College before the SC.

A midday recovery at King Salmon reduced what otherwise would have been a large post-SC increase of absorption. This midday recovery was also observed at College. King Salmon eventually did reach a near polar cap value of about 13 db around 05^h July 18. By the 14^h July 18, King Salmon registered about 1 db compared with 6 db at College. The

College/Thule ratio was generally about unity as late as the 21st, and hence it is clear that the cutoff did not dominate the situation at College. During the midday recovery on the 18th, at about 1800^h, the College/Thule ratio was about .85. The balloon flights of Anderson and Enemark(14) shows that protons of energy greater than 90 MeV were arriving at the earth more than 9 days after the original flare. Some other aspects of the riometer data for the events of May and July 1959 have been discussed elsewhere [Reid and Leinbach(15); Leinbach and Reid(16)].

SUMMARY, DISCUSSION, AND CONCLUSIONS

The events discussed in this paper are representative examples of the many PCA events observed by riometers since 1957. The events discussed here are particularly interesting since only meager satellite data, or none at all, are available to fix the cutoff energy at College. The essential basis of our interpretation is the ratio of the observed absorption at College to that at Thule. The accuracy of this ratio depends on both random and systematic errors in the absorption derived for either station. A detailed discussion by Leinbach(3) shows that the maximum possible errors do not exceed 10% to 20% for moderate values of absorption, say 2 to 10 db.

One must also recognize that periods of auroral absorption at College increase the ratio of C/T over that due to the polar cap contribution alone. Similarly, the nighttime decrease of absorption at either station leads to anomalous ratios of the polar cap absorption.

In this study, we have used the ratio C/T for those times when (a) both stations were sunlit, and (b) there was no evidence of pronounced auroral absorption at College. In addition, if the auroral absorption contribution could be estimated (for example, because of its time structure), we have taken the underlying steady level of absorption to represent the PCA contribution, and used those values to determine the ratio C/T.

The ratios C/T for three events best suited for comparison are given in Figure 11. An example of the scatter to be expected in the hourly ratios C/T for the average event with low to moderate auroral activity at College is seen in Figure 11A. Figures 11B and 11C show the plots of the ratios C/T for two more events discussed in this paper, after allowance has been made for the presence of auroral absorption and nighttime recovery. One should note that the correction for the auroral absorption actually lowers the ratio C/T. Thus the conclusions we derive below concerning the low effective cutoff energy at College is based on the minimum probable values of the ratio C/T.

The present study leads to the following generalizations:

(a) The ratio C/T is relatively independent of the ring current, as measured by D_{st}. The ratios C/T were always greater than 0.5, and usually exceeded 0.8, even during the recovery phase of the events.

(b) The presence of polar cap absorption at the stations of Farewell and King Salmon (2 and 7 degrees south of College, respectively) was closely connected with the magnetic activity, as measured by D_{st}. In general, Farewell reached the full polar cap value of absorption only in those storms which eventually attained maximum D_{st} values of 100 γ or more, and similarly, King Salmon for maximum D_{st} values in excess of 200 γ. For storms whose maximum value of D_{st} was less than 200 γ, the time of the maximum value of polar cap absorption at King Salmon corresponded approximately with the time of maximum D_{st}.

(c) The value of D_{st} at the time of the magnetic storm increase of polar cap absorption at Farewell and King Salmon was smaller than the D_{st} values at the time when the absorption recovered to its prestorm value.

In the discussion below, we first give the theoretical interpretation of the ratio C/T. We then examine the above points in detail, relative to the theoretical study, and to the findings of other investigators.

Theoretical values of the ratio of absorption at College to that at Thule can be estimated by (a) assuming the shape of the energy spectrum, (b) taking the Thule cutoff to be zero, and (c) assuming that the inherent cutoff in the solar flux of particles is of the order of 1 MeV or less. The last assumption is not directly defensible from the riometer data alone. However, none of the proton events studied with low energy (30 MeV or less) proton detectors on board satellites and space probes have shown inherent cutoffs in the beam greater than the instrumental cutoff. (Of course, the velocity dispersion of the particles means that the low energy particles do not arrive until after the high energy particles. This absence of the low energy particles during the initial phase of the event would tend to raise the ratio C/T to unity.)

The details of the calculation of absorption from a given spectrum are discussed in a number of papers, a useful summary of which is given by Bailey(2). We make use of Bailey's Figure 3 (reproduced here as Figure 12) in which he gives the calculated total absorption for four different exponential rigidity spectra. Further on, we show that the alternate assumption that the spectrum is a power law in energy <u>does not</u> change our basic conclusion about the significance of the ratio C/T. In this connection it is noteworthy that, regardless of the spectral law, protons of energies as low as 5 MeV make a significant contribution to the total absorption in any case where the spectrum is still rising at the low energies. It is also instructive to note that for a perfectly flat spectrum (equal flux of particles at each energy), the maximum contribution to the absorption is from 30 MeV protons, or 120 MeV alphas [Van Allen, Lin, and Leinbach(17)].

From Bailey's curves one can find the amount of absorption expected for any given cutoff energy for the specific profiles presented. If the spectrum does not change in shape, but only in the total number of particles, then the absorption at two different flux levels, but with the same cutoff, are related simply by

$$A(1)/A(2) = (J_o(1)/J_o(2))^{1/2}$$

where J_o is characteristic of the integral exponential rigidity spectrum:

$$J(P) = J_o e^{-P/P_o}$$

[e.g., Bailey(2)]. Thus one can easily scale the absorption corresponding to desired J_o values, for those spectra with P_o values used by Bailey.

Table II gives the cutoff energies corresponding to given values of the ratio of absorption at a station with cutoff E_c to that at a station with zero cutoff energy (as assumed for Thule, Greenland). The four spectra used by Bailey, characterized by P_o = 45, 65, 140, and 280 MV, respectively, probably encompass the range of most solar proton events. Spectra as hard as that characterized by P_o = 280 MV (May 4, 1960) are rare, and with the possible exception of the first hours of an event, most PCA events are better characterized by values of $P_o < 150$ MV [Freier and Webber(18)]. Calculations of absorption based on model spectra are known to be uncertain insofar as the rate processes of recombination in the lower atmosphere are only imperfectly understood. An indication of the extent of uncertainty may be seen by reference to a similar set of calculations due to Webber(1), as summarized in Table III.

Comparing the cutoff energies listed in Table II for given ratios C/T with the actual polar cap data, it becomes apparent that the cutoff at College must normally be 35 MeV or less, and often as low as 10 MeV (since $C/T \geq 0.5$ and usually is closer to .9).

For the sake of illustration, we have used calculations based on an exponential rigidity spectrum. The other extreme of the possible spectra would be a power law in energy. For this type of spectrum, the relative numbers of low energy particles are increased over that specified by the exponential spectrum. The net effect on the absorption would be to markedly decrease the ratio C/T if College has any cutoff other than zero. Thus the observed high ratios C/T would of necessity imply a very low cutoff at College for a power law spectrum. This aspect of power law spectra was pointed out long ago by Bailey(19). [See also Frier and Webber(18), Figure 13.]

From the above discussion, we can conclude that regardless of whether the actual spectrum is best described by an exponential rigidity spectrum or by a power law spectrum or by any reasonable intermediate type of spectrum, the observed high values of the ratios C/T imply that the effective cutoff energy at College for protons is 35 MeV or less.

It is apparent that a high ratio C/T (≥ 0.8) and the independence of the course of the PCA at College on D_{st} are self-consistent facts. For if College observed essentially the full polar cap intensity of particles before a magnetic storm, then no further increase of flux relative to the polar value could follow during the storm.

Our conclusion that the College cutoff usually is less than 35 MeV is also consistent with the direct measurements of solar protons made by Explorer VII during 1960. Akasofu, Van Allen, and Lin(20), for example, plotted L_{min} (the value of L at the knee of the proton intensity vs L curves) as a function of the U parameter [Kertz(21)], a measure similar to D_{st}. The instrumental cutoff of the lowest energy Geiger tube used in their work was 30 MeV. For this effective cutoff, it was found that the knee value L_{min} was about 5.7, extrapolating the experimental curve to $U = 0\ \gamma$. Since the L value of College is 5.5, one concludes that D_{st} should therefore have no influence on the flux of particles of energies greater than 30 MeV incident over College. Observations of the proton events of July 1961 have shown directly that the College cutoff may be as low as 0.5 MeV [Maehlum and O'Brien(22)].

From the study of Akasofu et al.(20), L_{min} is reduced to 4.3 (corresponding to Farewell) when $U \approx 110\ \gamma$, while L_{min} of 3.3 (corresponding to King Salmon) requires $U \simeq 190\ \gamma$. Again, these values of U are consistent with our observation that full polar cap absorption is not reached at Farewell unless D_{st} reaches at least 100 γ, while D_{st} of at least 200 γ is required to produce full polar cap intensity of absorption at King Salmon.

In making a quantitative comparison of the results of Akasofu et al.(20) with the actual absorption, one would have to account for the relative contribution of protons of energies less than 30 MeV to the absorption. Van Allen, Lin, and Leinbach(17) have shown that these low energy particles are indeed important, by direct comparison of Explorer VII data with riometer data.

An estimate of the change in cutoff at Farewell between quiet conditions and very disturbed conditions can be extrapolated from Table II. Prior to magnetic activity, Farewell generally exhibits about 0.14 of the value of absorption at Thule. Thus the proton cutoff energy for Farewell cannot be less than about 50 MeV, even for the steepest spectrum, and probably lies closer to 100 to 200 MeV. Note that this estimated pre-storm value is still appreciably below the dipole cutoff value of 262 MeV.

On the other hand, Farewell shows essentially full polar cap absorption when the magnetic activity reaches values of $D_{st} \sim 100\text{-}150$ gamma. Thus at these times the cutoff must be reduced to well below 30 MeV, in accord with Akasofu, Lin, and Van Allen's(20) earlier deduction.

King Salmon does not show full polar cap intensity of absorption unless the magnetic storm eventually obtains a D_{st} value of at least 200 gammas. This statement appears to be true regardless of the value of D_{st} at the time when the absorption begins, which can be much less than 200 gammas. The significance of this fact is not clear. However, it is true that D_{st} does not give a complete specification of the ring current, since both the magnitude and the position of the ring current determine the perturbation experienced at the earth's surface [e.g., Akasofu and Lin(5), particularly their Figure 1].

It is also of interest that the absorption at King Salmon begins to recover while D_{st} values are relatively large, certainly much greater than the corresponding value of D_{st} at the onset of the absorption. This effect may simply be a consequence of the well-known softening of the particle spectrum during the course of the event.

Finally, we want to point out a practical consequence of our conclusion that the College cutoff is always reduced to values of the order of 30 MeV or less (at least during the active part of the sunspot cycle). It is apparent that to a good approximation, one can estimate the polar cap absorption expected at a polar station of zero cutoff, from observations made in and near the auroral zone, such as at College, Alaska, or Kiruna, Sweden, or the Canadian auroral zone stations. Since these stations have relatively direct and easy communications with the rest of the world, they can thus continue to serve in the useful capacity of giving early warnings that a major solar proton event is in progress, even to estimating the relative magnitude of the event. A major difficulty in extracting PCA data from stations in the auroral zone, however, remains one of removing the contamination of auroral zone absorption events.

TABLE I

Location of the IGY Riometers Operated by the Geophysical Institute, University of Alaska

	Geographic		Geomagnetic		
	Latitude	Longitude	Latitude	Longitude	
Thule	76°33'N	68°50'W	88.0° N	1.0° E	
Barrow	71°31'N	156°20'W	68.5° N	241.25°E	7.8
Ft. Yukon	66°34'N	145°18'W	66.69°N	257.05°E	6.4
College	64°52'N	147°49'W	64.65°N	256.56°E	5.5
Farewell	62°30'N	153°52'W	61.4° N	253.42°E	4.25
King Salmon	58°41'N	156.37'W	57.45°N	254.9° E	3.3

TABLE II

Proton Cutoff Energies for Different Exponential Rigidity Spectra and Ratios of Absorption at a Station to that of a Station of Zero Cutoff Energy

Ratio $\frac{A(E_c)}{A(0)}$	E_c (MeV)			
	P_0=65 MV (1) May 12, 1959	140 MV (2) Feb. 23, 1956	45 MV (3) July 14, 1961	280 MV (4) May 4, 1960
	MeV	MeV	MeV	MeV
1.0	0	0	0	0
.8	15	17	12	20
.6	23	32	17	42
.4	34	55	25	80
.2	55	110	39	160 (extrapolated)

After Figure 3, Bailey(2).

TABLE III

Proton Cutoff Energies for Different Exponential Rigidity Spectra and Ratios of Absorption at a Station to that of a Station of Zero Cutoff Energy

Ratio $\frac{A(E_c)}{A(0)}$	P_o = 50 MV	100 MV	150 MV
	MeV	MeV	MeV
1.0	0	0	0
.8	12	22	22
.6	22	30	50
.4	40	70	105
.2	70	112	190

Webber: Figure 9
[J. Geophys. Res., 67, 5104, 1962]

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FIGURE CAPTIONS

Figure 1. PCA event of March 23, 1958.

Figure 2. PCA event of April 10, 1958.

Figure 3. PCA event of July 7, 1958.

Figure 4. PCA event of August 16, 1958.

Figure 5. PCA events of August 21 and 22, 1958.

Figure 6. PCA event of August 26, 1958.

Figure 7. PCA event of May 11, 1959.

Figure 8. PCA event of July 10, 1959. Note that the dynamic range of the Thule riometer was about 12 db for the July 1959 events.

Figure 9. PCA event of July 14, 1959.

Figure 10. PCA event of July 16, 1959.

Figure 11. Plots of the ratio C/T and corresponding D_{st} values for three PCA events.

a. July 8-10, 1958, showing the typical scatter of the ratio C/T.

b. Smoothed values of C/T for July 18-21, 1959.

c. Smoothed values of C/T for May 12-16, 1959.

Figure 12. The relation between integral proton intensity above cutoff (MeV) and the daytime polar-cap absorption indicated by a 30 Mc/s riometer at locations with the indicated cutoffs. Four exponential rigidity spectra characterized by:

Curve 1 $P_o = 65$ MV Curve 3 $P_o = 45$ MV

Curve 2 $P_o = 140$ MV Curve 4 $P_o = 280$ MV

[Bailey(2), Figure 3].

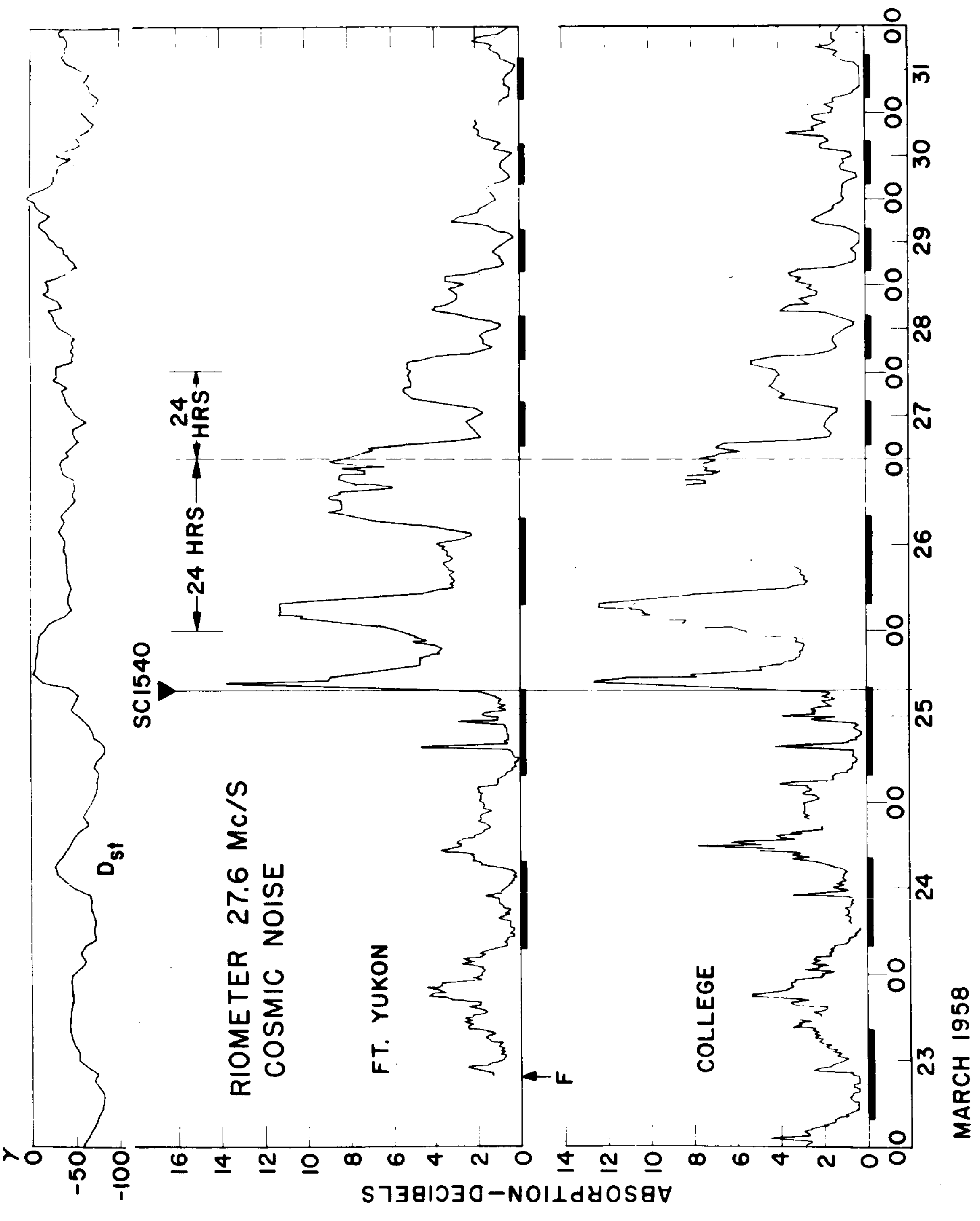

γ
0
-50
-100
ABSORPTION—DECIBELS
16
14
12
10
8
6
4
2
0
14
12
10
8
6
4
2
0
D$_{st}$
SC1540
24 HRS
24 HRS
RIOMETER 27.6 Mc/S
COSMIC NOISE
FT. YUKON
F
COLLEGE
00
23
00
24
00
25
00
26
00
27
00
28
00
29
00
30
00
31
00
MARCH 1958

Figure 1

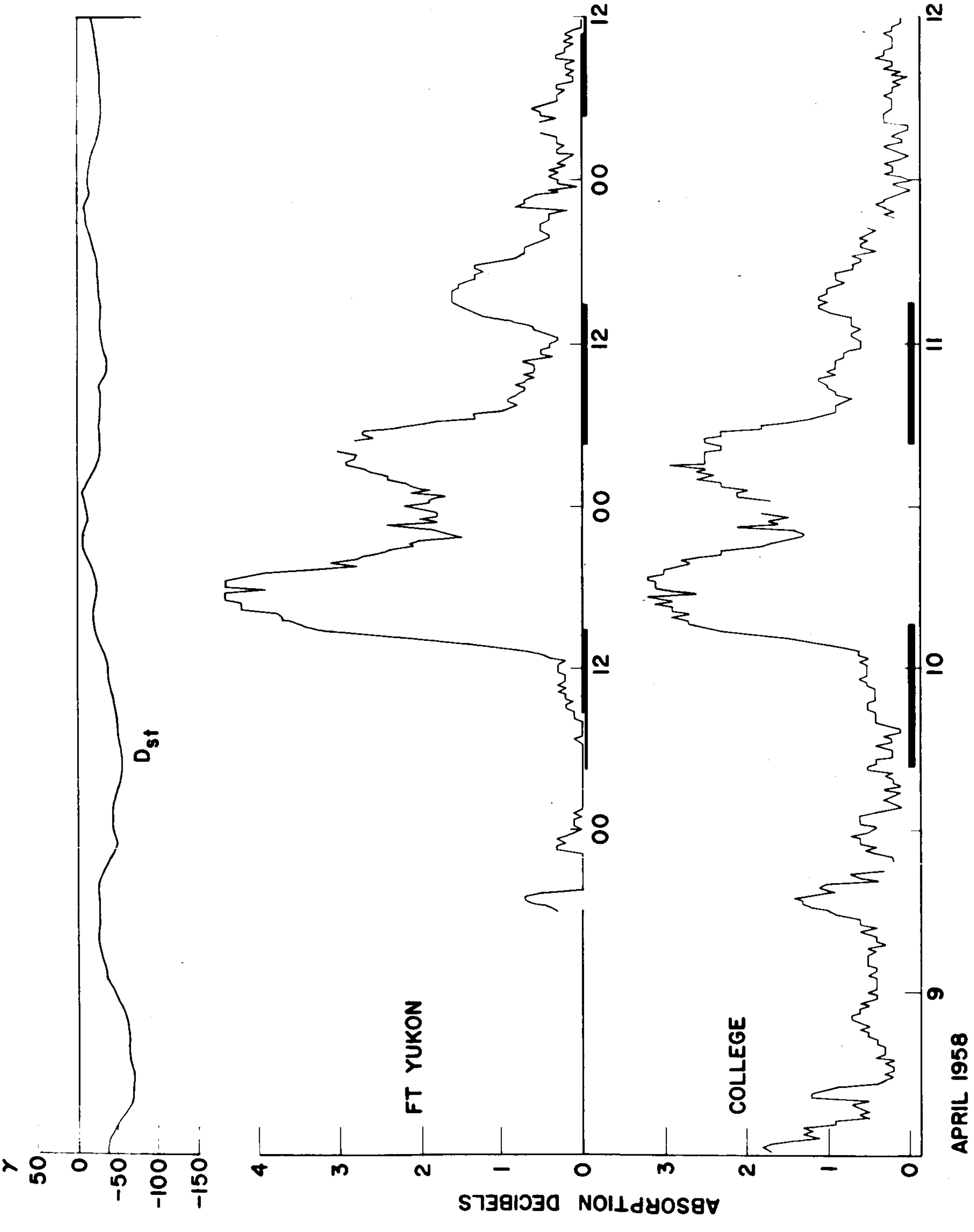
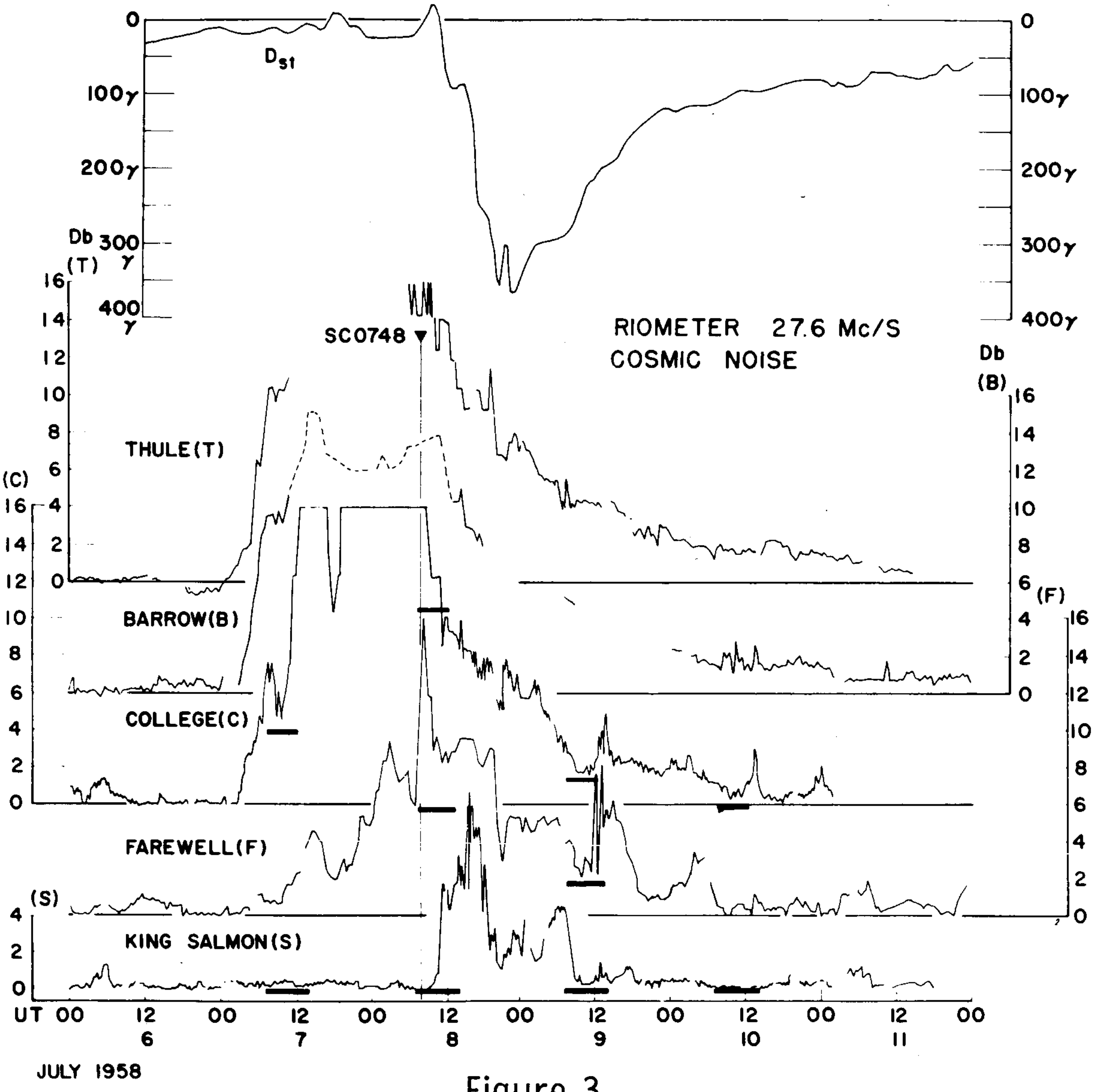
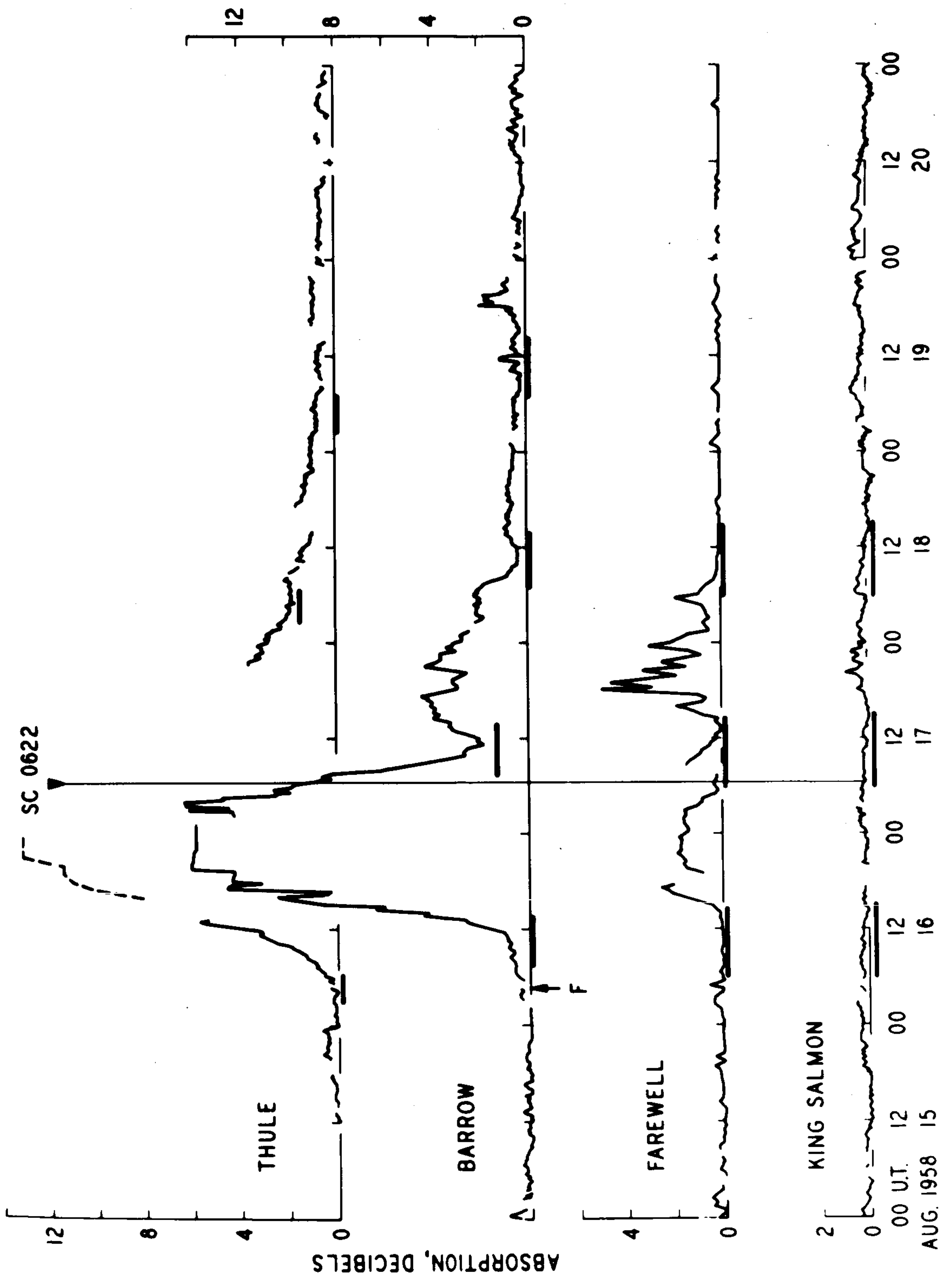

γ
50
0
-50
-100
-150
D_st
ABSORPTION DECIBELS
4
3
2
1
0
3
2
1
0
FT YUKON
COLLEGE
00
12
00
12
00
12
9
10
11
12
APRIL 1958

Figure 2



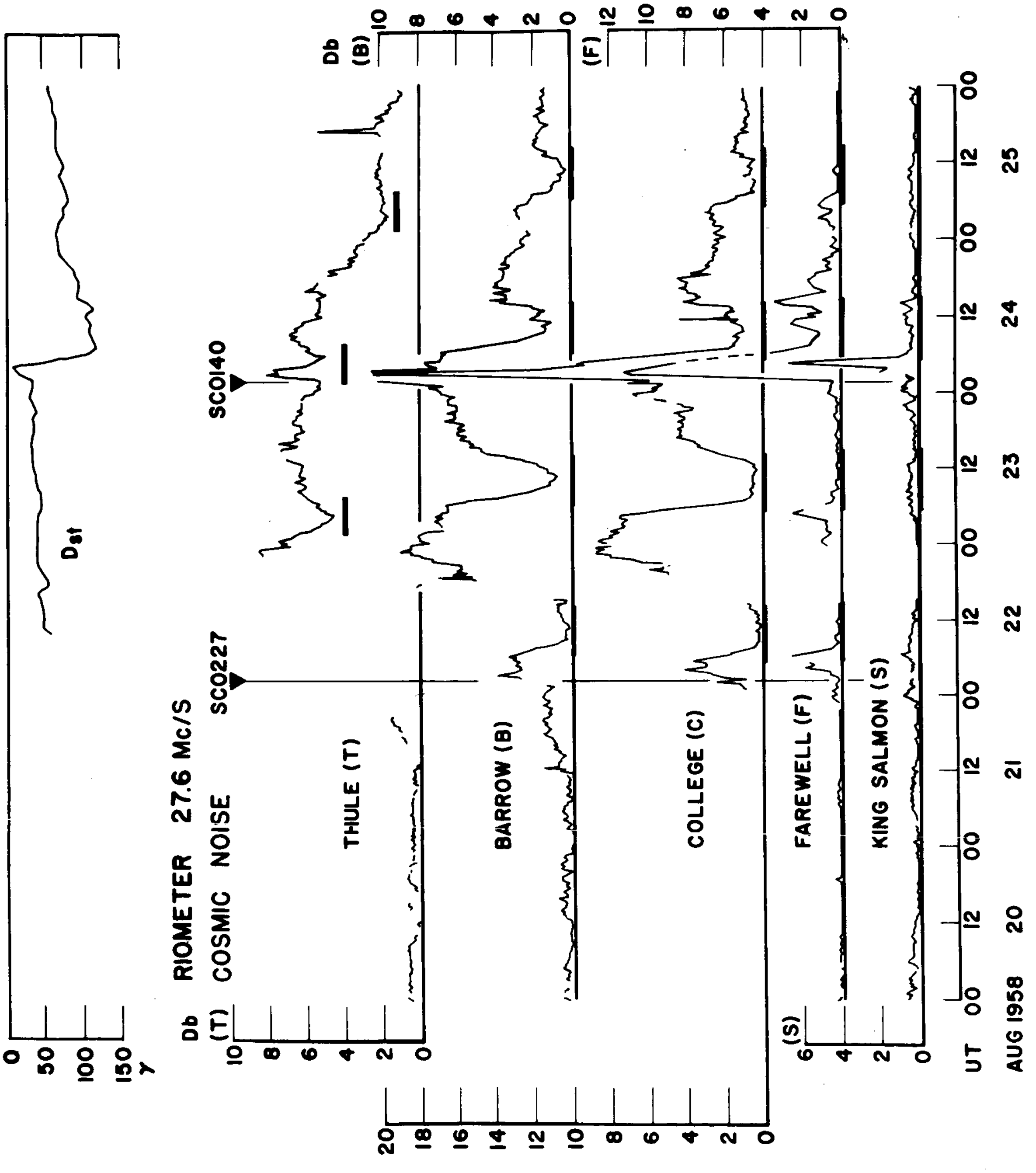
0
100γ
200γ
300 γ
400 γ
Dst
Db (T)
16
14
12
10
8
6
4
2
0
SC0748
RIOMETER 27.6 Mc/S
COSMIC NOISE
THULE(T)
(C)
BARROW(B)
COLLEGE(C)
FAREWELL(F)
(S)
KING SALMON(S)
Db (B)
(F)
UT 00 12 00 12 00 12 00 12 00 12 00 12 00
6 7 8 9 10 11
JULY 1958

Figure 3



PCA of August 16, 1958.

Figure 4



0
50
100
150
γ
D$_{st}$
RIOMETER 27.6 Mc/S
COSMIC NOISE
SC0227
SC0140
THULE (T)
BARROW (B)
COLLEGE (C)
FAREWELL (F)
KING SALMON (S)
Db
(T)
10 8 6 4 2 0
Db
(B)
10 8 6 4 2 0
(F)
12 10 8 6 4 2 0
(S)
6 4 2 0
20 18 16 14 12 10 8 6 4 2 0
UT 00 12 00 12 00 12 00 12 00 12 00 12 00
AUG 1958 20 21 22 23 24 25

Figure 5

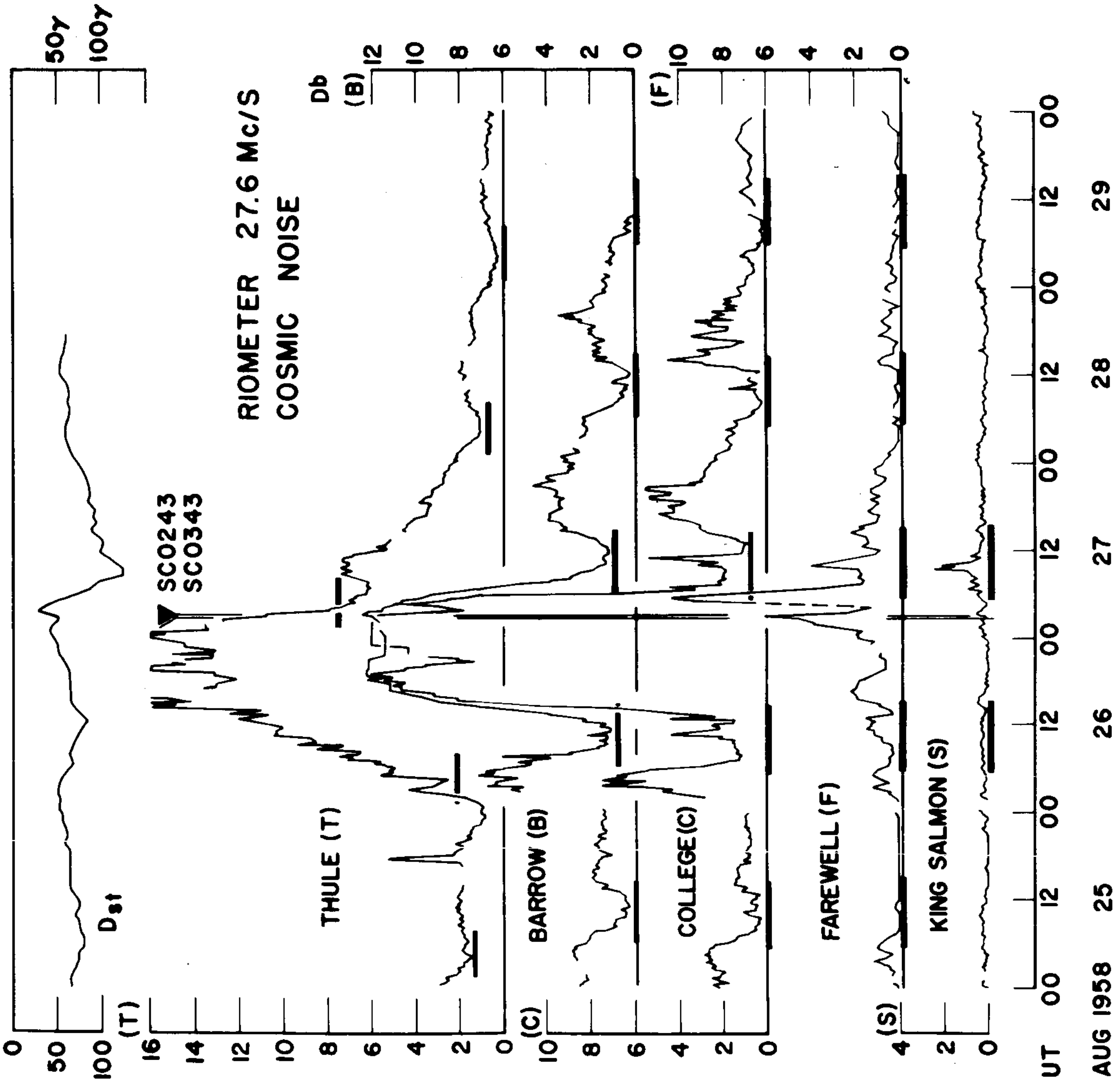

RIOMETER 27.6 Mc/S
COSMIC NOISE
D_{st}
0
50
100
50γ
100γ
SC0243
SC0343
Db
(T)
16
14
12
10
8
6
4
2
0
(B)
12
10
8
6
4
2
0
(C)
10
8
6
4
2
0
(F)
10
8
6
4
2
0
(S)
4
2
0
THULE (T)
BARROW (B)
COLLEGE (C)
FAREWELL (F)
KING SALMON (S)
UT
00
12
00
12
00
12
00
12
00
12
00
AUG 1958
25
26
27
28
29

Figure 6

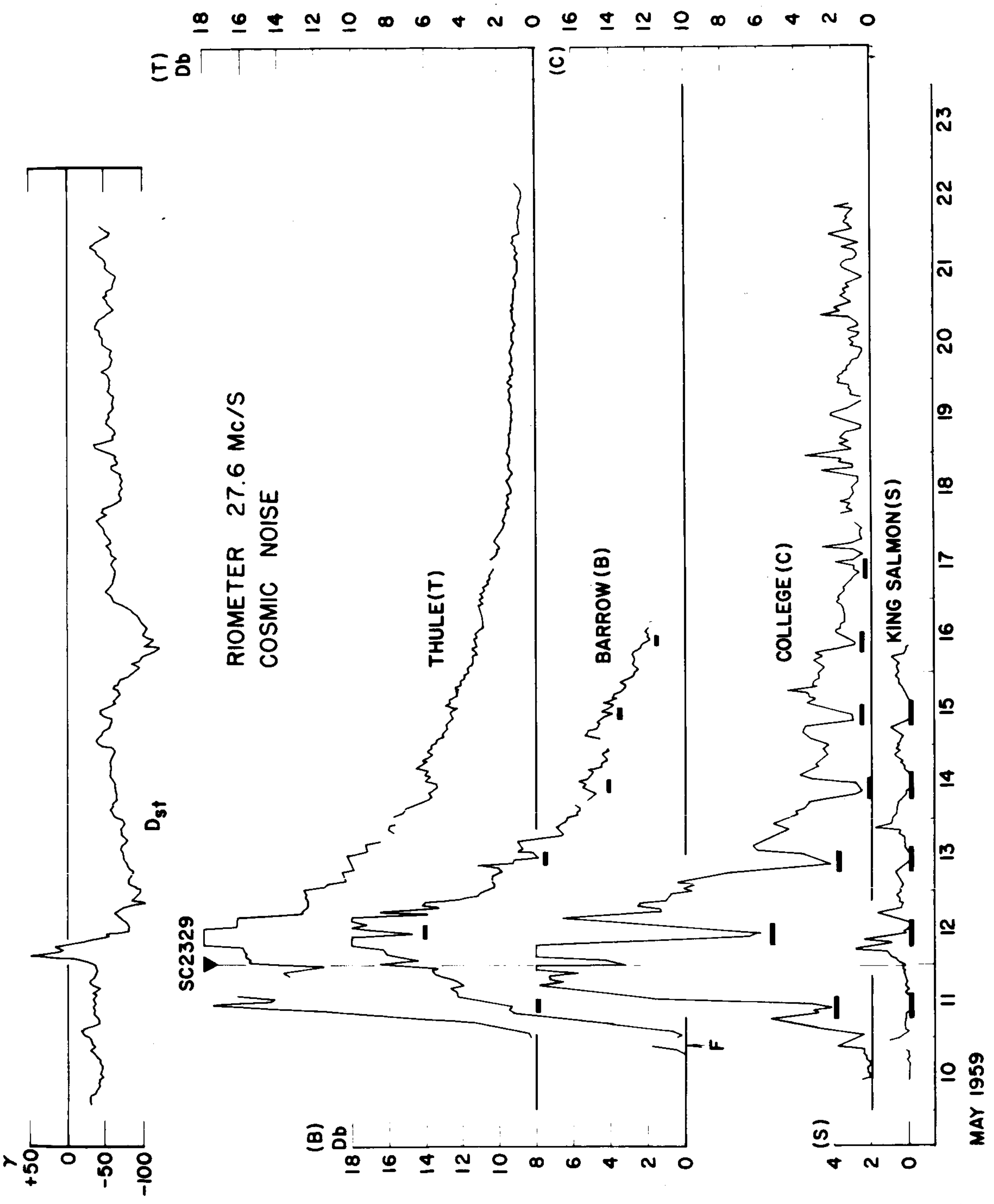
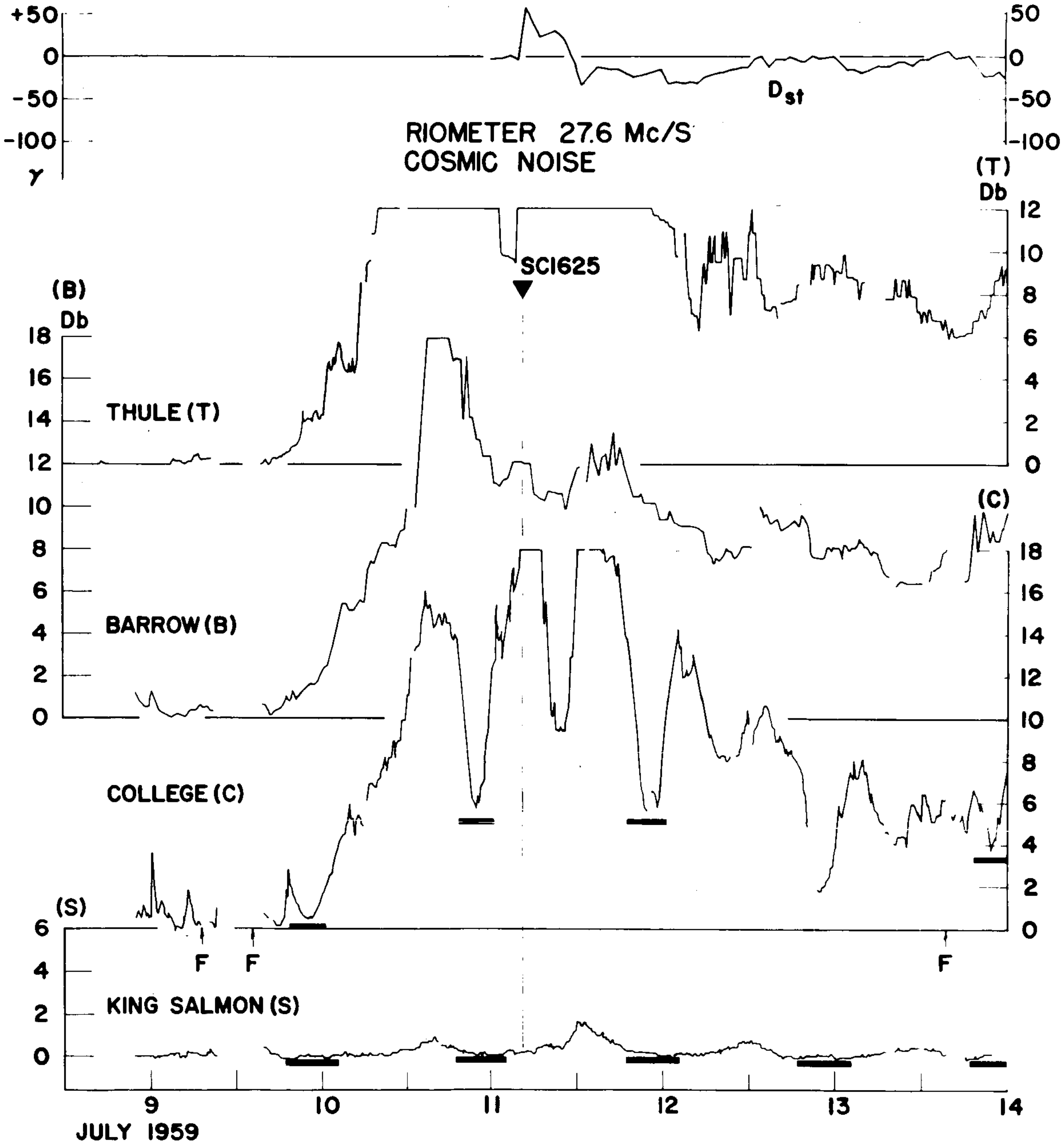

RIOMETER 27.6 Mc/S
COSMIC NOISE
THULE(T)
BARROW(B)
COLLEGE(C)
KING SALMON(S)
Dst
SC2329
F
γ
+50
0
-50
-100
(B)
Db
18
16
14
12
10
8
6
4
2
0
(S)
4
2
0
(T)
Db
(C)
10
11
12
13
14
15
16
17
18
19
20
21
22
23
MAY 1959

Figure 7



+50
0
-50
-100
γ
50
0
-50
-100
D_st
RIOMETER 27.6 Mc/S
COSMIC NOISE
(T)
Db
12
10
8
6
4
2
0
SC1625
(B)
Db
18
16
14
12
10
8
6
4
2
0
THULE (T)
BARROW (B)
COLLEGE (C)
(C)
18
16
14
12
10
8
6
4
2
0
(S)
6
4
2
0
F
F
F
KING SALMON (S)
9
10
11
12
13
14
JULY 1959

Figure 8

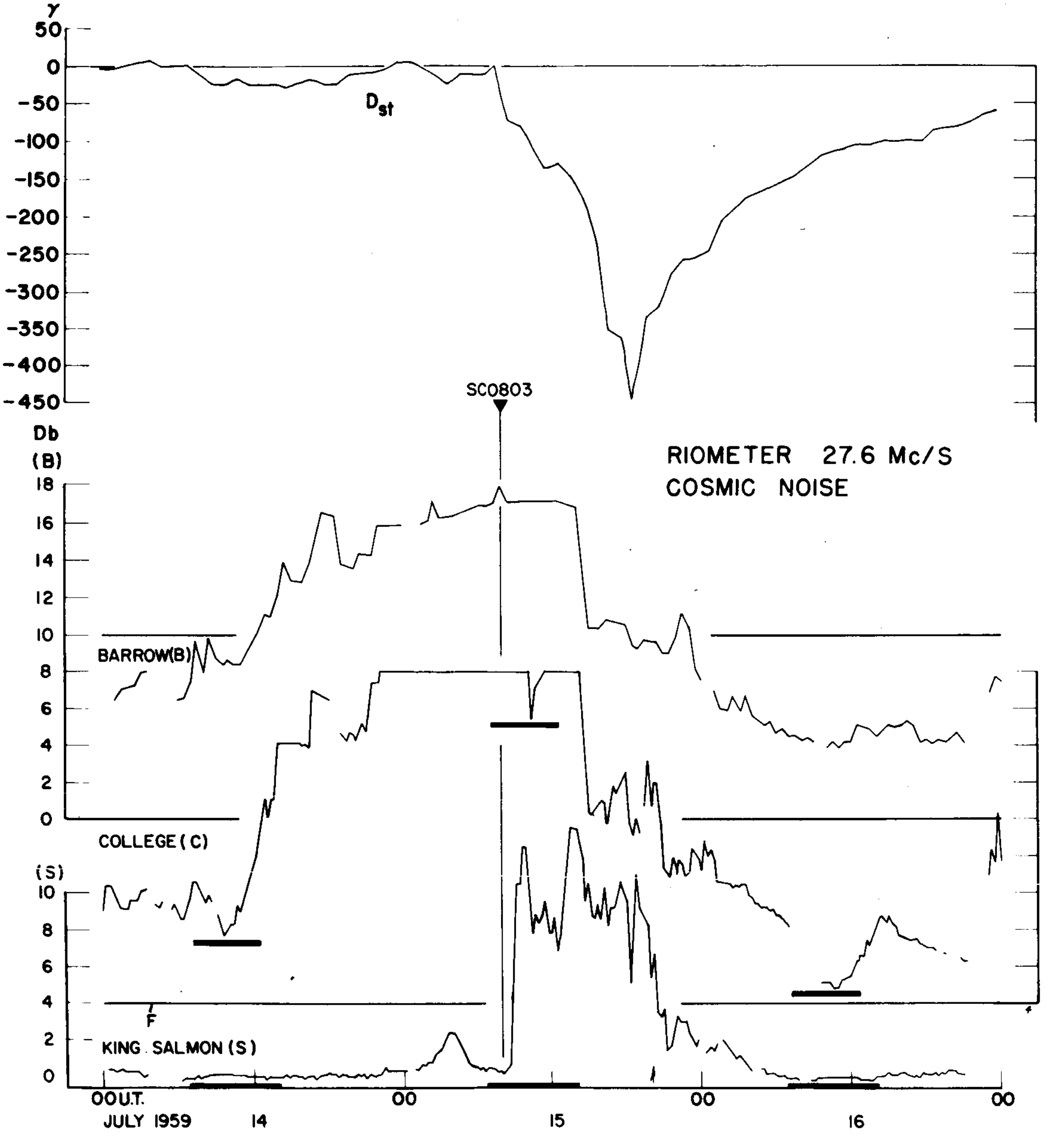

γ
50
0
-50
-100
-150
-200
-250
-300
-350
-400
-450
D_{st}
SC0803
Db
(B)
18
16
14
12
10
8
6
4
2
0
RIOMETER 27.6 Mc/S
COSMIC NOISE
BARROW(B)
COLLEGE (C)
(S)
10
8
6
4
2
0
KING SALMON (S)
F
Db
(C)
18
16
14
12
10
8
6
4
2
0
00 U.T.
JULY 1959
14
00
15
00
16
00

Figure 9

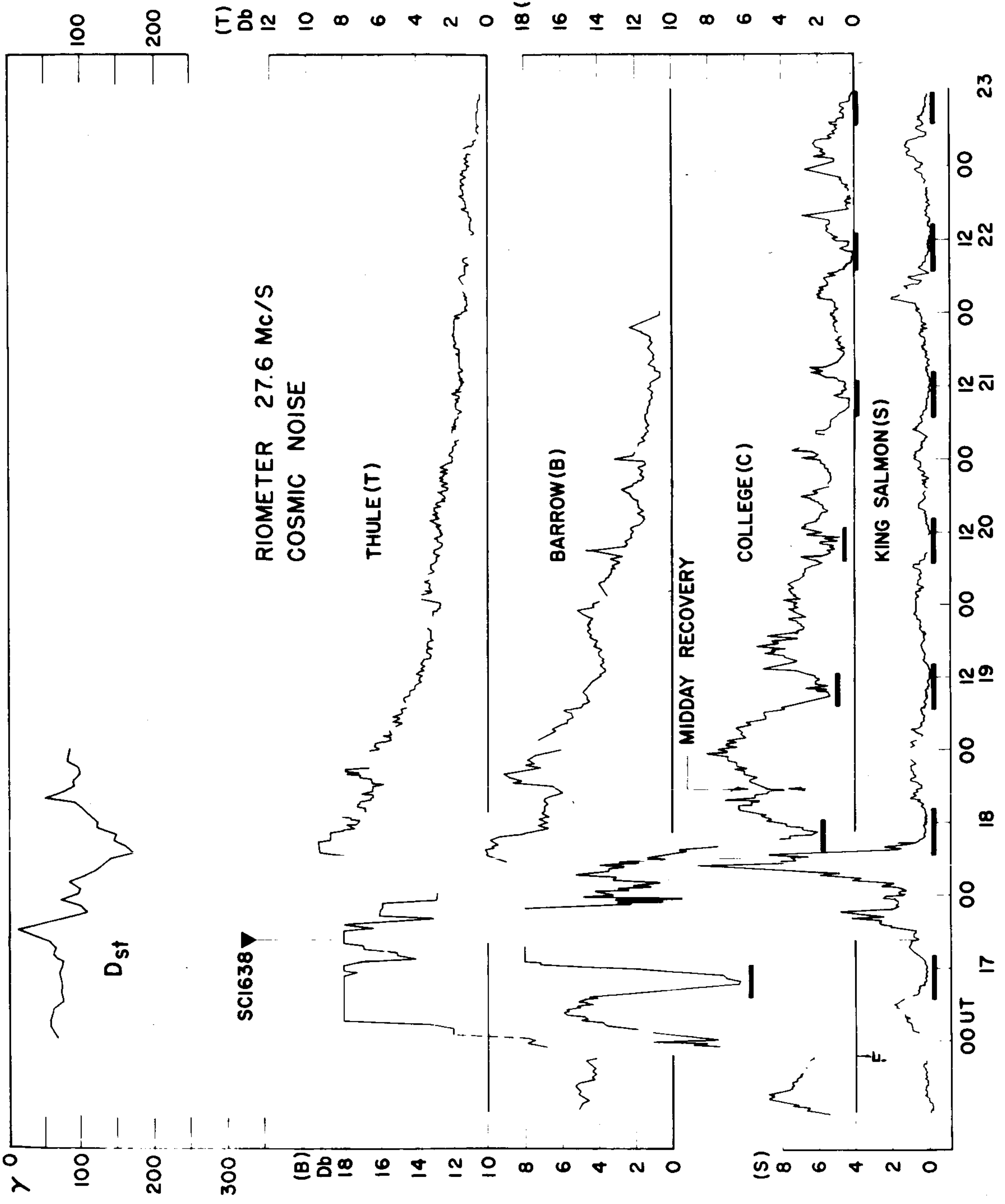

RIOMETER 27.6 Mc/S
COSMIC NOISE
Dst
SC1638
THULE (T)
BARROW (B)
COLLEGE (C)
KING SALMON (S)
MIDDAY RECOVERY
F
γ
0
100
200
300
(B) Db
18
16
14
12
10
8
6
4
2
0
(S)
8
6
4
2
0
100
200
(T) Db
12
10
8
6
4
2
0
18 (C)
16
14
12
10
8
6
4
2
0
00 UT
17
00
18
00
12
19
00
12
20
00
12
21
00
12
22
00
23
JULY 1959

Figure 10

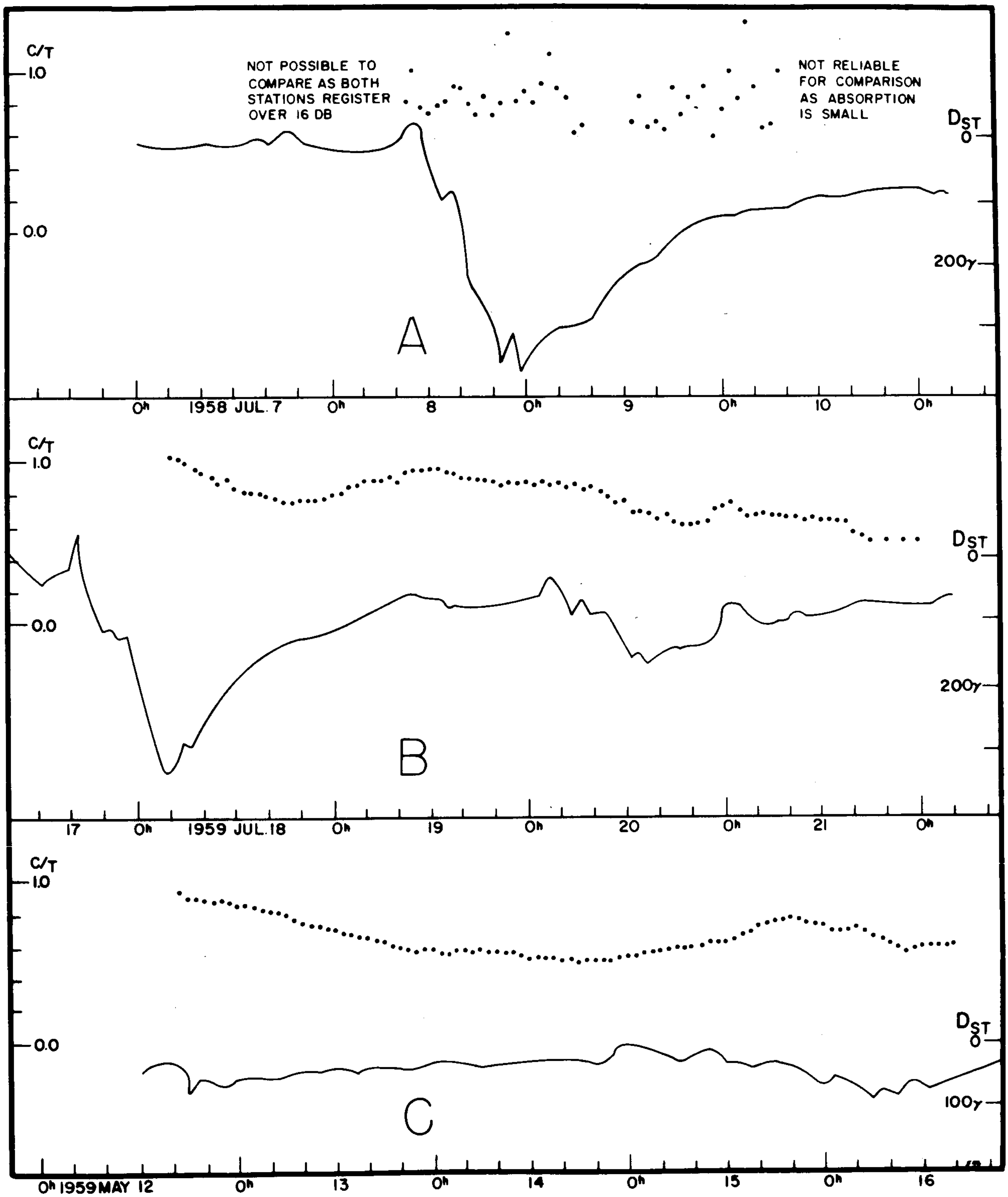

C/T
1.0
0.0
NOT POSSIBLE TO COMPARE AS BOTH STATIONS REGISTER OVER 16 DB
NOT RELIABLE FOR COMPARISON AS ABSORPTION IS SMALL
DST
0
200γ
A
0h
1958 JUL. 7
0h
8
0h
9
0h
10
0h
C/T
1.0
0.0
DST
0
200γ
B
17
0h
1959 JUL. 18
0h
19
0h
20
0h
21
0h
C/T
1.0
0.0
DST
0
100γ
C
0h 1959 MAY 12
0h
13
0h
14
0h
15
0h
16

Figure 11

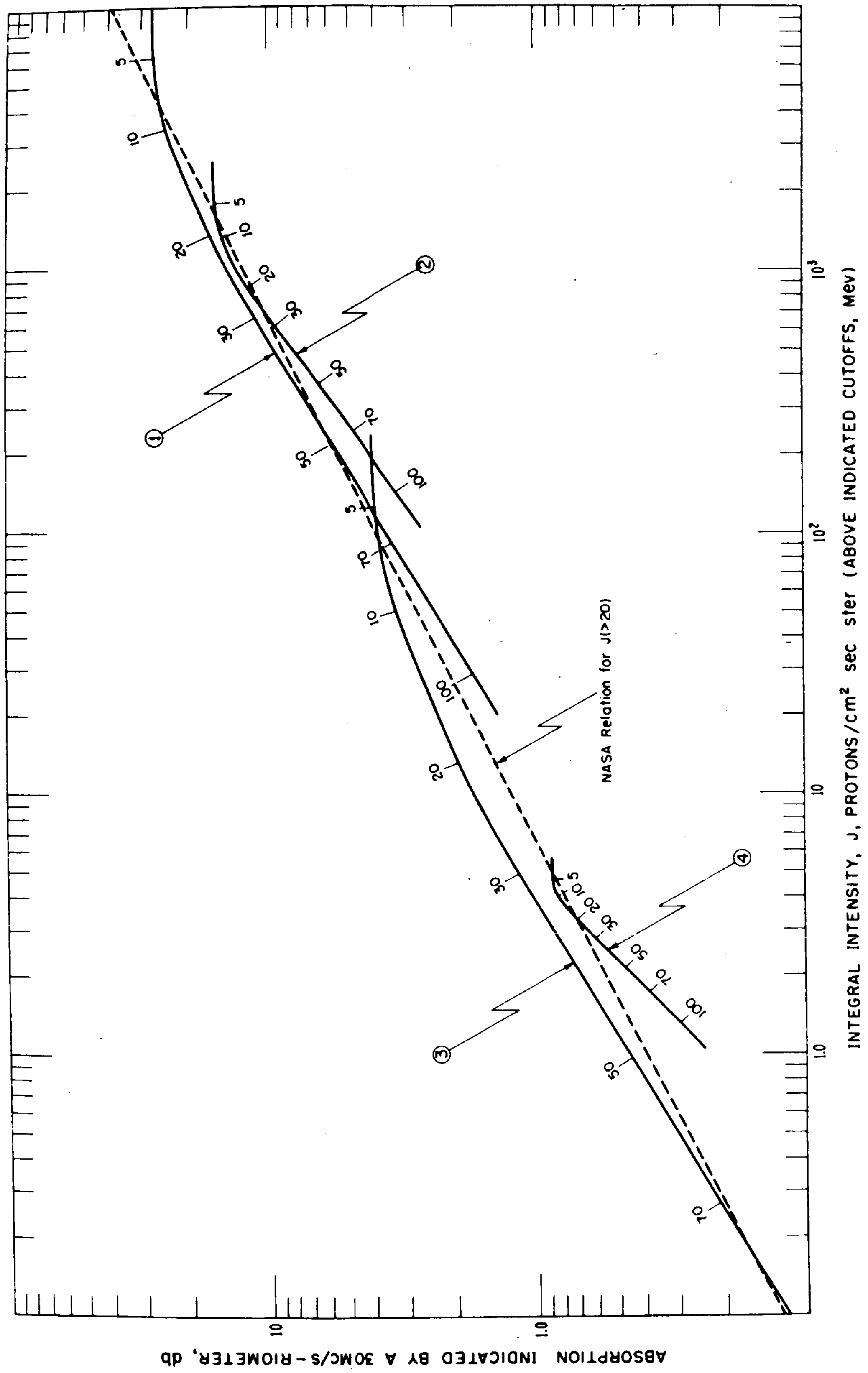

INTEGRAL INTENSITY, J, PROTONS/cm² sec ster (ABOVE INDICATED CUTOFFS, Mev)
1.0
10
10²
10³
ABSORPTION INDICATED BY A 30MC/S-RIOMETER, db
1.0
10
NASA Relation for J(>20)
①
②
③
④
5
10
20
30
50
70
100

Figure 12