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Direct Satellite Observations on Bremsstrahlung Radiation as a Technique to Investigate Its Role in Meteorological Processes

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It has been suggested by Roberts and Olson that bremsstrahlung radiation associated with strong auroras (in turn associated with geomagnetic disturbances) may cause increased ionization near the 300-millibar level, which, in turn, leads to the formation of cirrus clouds. These clouds could then modify the outgoing blackbody radiation rates and thus influence weather patterns. Recently, the first satellite observations on bremsstrahlung radiation produced in the atmosphere by precipitating energetic electrons have been reported by Imhof, Nakano, Johnson, and Reagan. This type of observation affords the possibility of directly monitoring the bremsstrahlung energy input to the lower atmosphere over large segments of Earth and at frequent intervals. Detailed measurements on the spatial and energy distributions of the bremsstrahlung radiation are feasible with present techniques and satellite data on widespread bremsstrahlung events are presented and discussed. From comparison of the ion production rates from cosmic rays with those calculated for bremsstrahlung from precipitating energetic electrons, it is concluded that bremsstrahlung radiation is a negligible contributor to the ionization near the 300-millibar level.

Recent results on the correlations between interplanetary magnetic sector boundaries and weather patterns (Wilcox et al., 1973) have provided added support for earlier evidence (Roberts and Olson, 1973*a*) of connections between solar activity and weather. The evidence for these connections has recently been reviewed by Roberts and Olson (1973*b*). Although various hypotheses have been advanced for the physical processes connecting the two phenomena, none has been generally accepted for lack of adequate experimental data and for lack of detailed understanding of atmospheric and magnetospheric processes. The purpose of this paper is to assess the validity of one such hypothesis and to discuss satellite observations and techniques that are pertinent to the investigation of the role of bremsstrahlung radiation in meteorological processes.

The first satellite observations on bremsstrahlung produced in the atmosphere by precipitating energetic electrons have recently been reported by Imhof et al. (1974). The bremsstrahlung measurements were obtained with a 50-cm^3 germanium spectrometer (a second spectrometer failed at launch) placed on the low-altitude, polar-orbiting satellite 1972–076B. The satellite was launched on October 2, 1972, into a Sun-synchronous noon-midnight orbit (inclination = 98.4°) with a perigee of 736 km and an apogee of 761 km. The satellite is spin stabilized with a rotation period of approximately 5 s and an onboard tape recorder provides capability for nearly worldwide coverage. The Ge(Li) detector cooling is achieved with a solid CO_2 cryogen system, and pulse-height analysis of the detector output provides energy spectra of the bremsstrahlung above 50 keV. The instrument is collimated to ±45° with a high-density (predominantly tungsten) shield and plastic-scintillator anticoincidence counter and is oriented at 75° to the spin axis of

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the satellite. The collimator is ~20 cm long, providing a relatively sharp cutoff angle and a geometric factor of 27 $cm^2 \cdot s$. Several energetic particle spectrometers provide spectral measurements on the energetic electron and proton fluxes. The details of the instrumentation are provided in other reports (Bakke et al., 1974; Imhof et al., 1973*a*; Nakano et al., 1974).

The geometry for observing the bremsstrahlung associated with electron precipitation is shown schematically for two spectrometers in figure 1 to illustrate that even at altitudes near 750 km, a large fraction of the region of electron precipitation at high magnetic latitudes can be observed. Because the satellite is spinning with a period that is very small compared to the time for traversal over a region of interest, the gamma-ray spectrometer scans the bremsstrahlung source distribution repeatedly. During a pass of the satellite over the polar cap, successive triangulations are made on each point within a large portion of the precipitation region. In figure 1 the shaded ellipses indicate schematically the fields of view of the spectrometers for different positions of the spinning satellite, and the shaded "band" indicates schematically a region from which bremsstrahlung is observed from electrons precipitating into the atmosphere. For future payloads designed especially to observe the bremsstrahlung, the extent of the region observed could be increased by widening the fields of view of the sensors or by increasing the satellite altitude. Thus, with current technology, the bremsstrahlung produced in the atmosphere by precipitating energetic electrons at the higher latitudes could be observed at all longitudes from a satellite about every 2 hr. From the energy distributions of the observed bremsstrahlung, the ion production rates as a function of altitude could then be calculated.

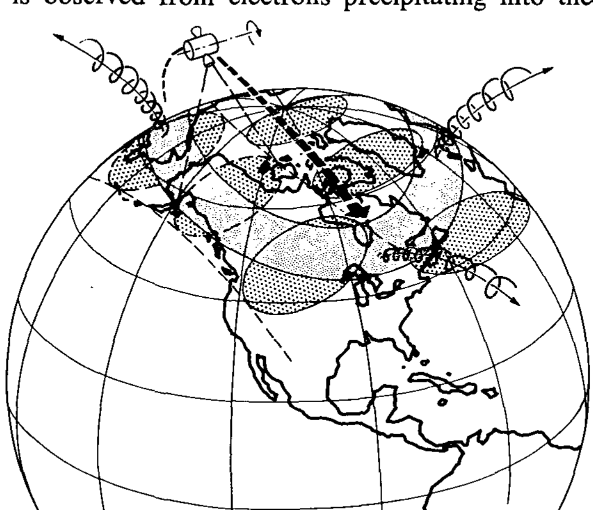

FIGURE 1.—Schematic illustration of the geometry for observing the bremsstrahlung associated with electron precipitation at high latitudes. The shaded ellipses indicate schematically the fields of view of the spectrometers for different positions of the spinning satellite, and the shaded "band" indicates schematically a region from which bremsstrahlung is observed.

An example of the bremsstrahlung and electron observations from the 1972–076B satellite is shown in figure 2. These data are from a pass over the northern polar region, and the location of the outer Van Allen radiation belt can be seen from the top curve showing a detector response to electrons with energies greater than 160 keV. The second curve from the top is the gamma ray spectrometer response to X-rays in the energy range from 50 to 75 keV. The large gamma ray response in the outer radiation belt is primarily from bremsstrahlung produced by the trapped electrons striking the shielding covering the collimator entrance. This response is generally modulated twice per spin period, reaching a maximum each time the spectrometer is oriented at 90° to Earth's magnetic field line. However, the gamma ray spectrometer shows an additional response on each side of the outer belt that is found from the satellite orientation data to come from below the satellite and to occur when the spectrometer is viewing regions of the atmosphere where electrons are precipitating. The third and fourth sections from the top show data from the polar cap region on expanded scales to illustrate the angular variation of the response with satellite position. The bottom sections are averaged over 24 successive spins to improve statistics. These data were taken during a magnetically disturbed period. Normally the levels of bremsstrahlung from the atmosphere are near or below the detectability threshold for the spectrometer. Because the energy threshold of the present gamma ray measurements is higher than that employed in many of the balloon observations and because the electron energy spectra are generally quite soft, the present data, in contrast to the bulk of the balloon measurements, are

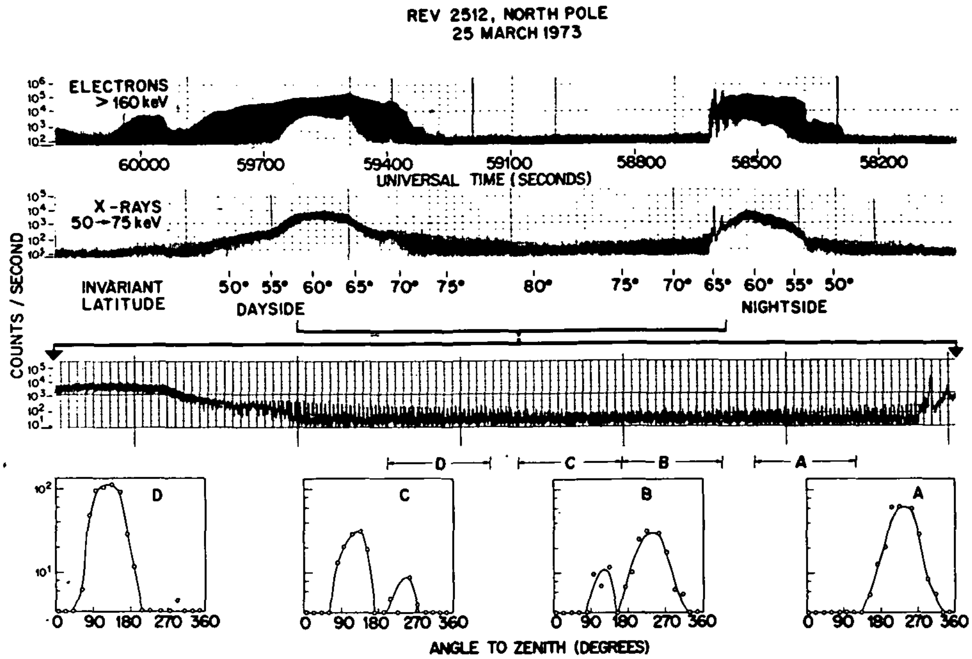

FIGURE 2.—The responses of the electron and gamma ray spectrometers during passage of the satellite over the north polar region at a time of great magnetic disturbance. The counting rates of X-rays in the energy range 50 to 75 keV are also shown for two different expanded time scales. In the bottom row, the counts have been grouped in angle intervals of 18°, and each angular distribution is summed and averaged over 24 spins.

more representative of very intense and more energetic precipitation from the outer radiation belt. Bremsstrahlung from auroral electrons, whose energy flux is typically dominated by electrons with energies below 20 keV (Sharp, Carr, and Johnson, 1969), would not be observed in the present experiment.

Using the measured gamma ray counting rate profiles and the known geometries of the gamma ray detector and the satellite, it is feasible to obtain information on the local time distribution of the bremsstrahlung from the atmosphere. Several examples of the local time dependencies of the precipitation levels as derived from the bremsstrahlung observations by least-squares-fitting techniques are shown in figure 3 (Imhof et al., 1974). The majority of these cases favor coverage in the morning hours. Because the satellite is in a noon-midnight orbit (descending node in daylight) and the viewing cone of the spectrometer is centered about a vector pointing 15° to the right of the satellite orbit plane, in the majority of passes the spectrometer responds primarily to sources located in the midnight-to-noon interval. Coverage with the spectrometer of the afternoon and early evening portions of the precipitation region is generally possible only for selected longitudes that are favorable as a result of the geomagnetic field axis being offset from Earth's spin axis. With the data from two spectrometers pointing in somewhat different directions, as illustrated schematically in figure 1, all local times can be covered with nearly equal probability.

In the limited number of cases shown, the bremsstrahlung radiation is found to be widespread in local time (or longitude) and the local time profiles display large variations in character. However, the precipitation levels near local noon are generally greater than in the early morning hours. In this regard the average time profiles of these individual intense and large-scale events are generally consistent with the time-averaged profiles obtained from localized measurements of the

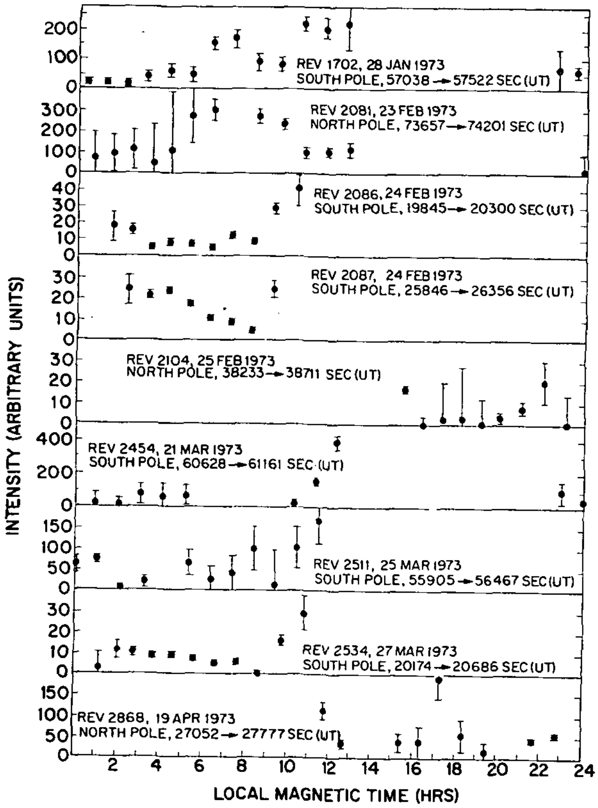

FIGURE 3.—The best fit intensities obtained from the least-squares-fit to the bremsstrahlung data plotted as a function of local magnetic time.

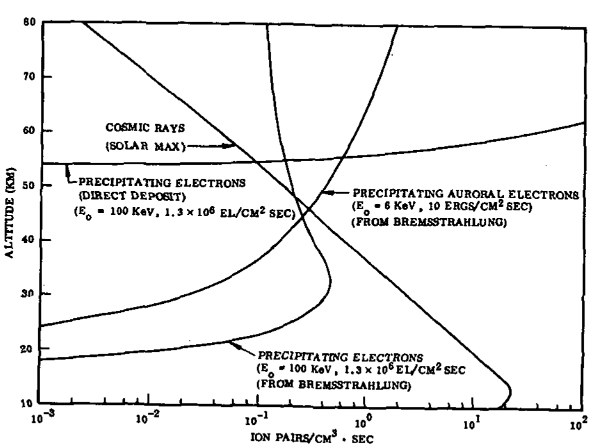

FIGURE 4.—The ion production rate as a function of altitude from the bremsstrahlung radiation and the direct deposit of energy by precipitating electrons with *e*-fold energies of 6 and 100 keV, respectively. The cosmic ray ion production rate at solar maximum is also shown (Webber, 1962).

precipitation of greater than 40-keV electrons (Imhof et al., 1974).

To explain the correlation between geomagnetic disturbances and weather cell characteristics, Roberts and Olson (1973*a*) have suggested that bremsstrahlung radiation associated with strong auroras may cause increased ionization near the 300-millibar level, which in turn could lead to the formation of cirrus clouds. To test this hypothesis, the ion production rates from bremsstrahlung radiation have been calculated as a function of altitude for several typical spectra of electrons precipitating into the atmosphere and for some of the bremsstrahlung spectra observed from the 1972–076B satellite. The general agreement between the observed bremsstrahlung spectra and the bremsstrahlung spectra calculated from the precipitating electron fluxes measured on the same satellite have been reported by Imhof et al. (1974). Two examples of the ion production rate calculations along with the cosmic ray ion production rate at solar maximum (Webber, 1962) are shown in figure 4. The cosmic ray production at high latitudes during solar minimum is about three times higher. The ion production rate for bremsstrahlung from the "auroral" electrons is shown for an electron energy distribution that is exponential in form and has a characteristic energy E_0 of 6 keV. The intensity of 10 ergs/cm^2 · s corresponds to an aurora of moderate intensity and is about a factor of 10 higher than the average nightside auroral particle energy input for the magnetic latitudes of 65° to 70° during a 4-day period that was moderately active magnetically (geomagnetic activity index K_p varied from 0_+ to 8_0) (Sharp, Carr, and Johnson, 1969). The characteristic energy, E_0, for these data, when fit with an exponential spectral form, averaged about 6 keV. It is seen from figure 4 that the ion production rate resulting from the "auroral" electron spectrum is about 10 percent the cosmic ray ion production rate at 37 km and the percent decreases rapidly at lower altitudes. The direct ionization from auroral electrons occurs principally at altitudes above 90 km.

The calculated ion production rate is also shown in figure 4 for an electron spectrum of exponential form with E_0 equal to 100 keV and a flux of 1.3×10^6 electrons/cm^2 · s. This intensity is the median value of the maximum encountered on several satellite passes during times of high geomagnetic disturbance on February 23, 1973, and March 20, 1973. Although the precipitating fluxes are sometimes larger by an order of magnitude (Imhof et al., 1973*b*; Rosenberg et al., 1972), such fluxes occur relatively infrequently compared to those used in the calculations. It is seen that the direct ion production rate by these electrons is larger than the cosmic ray ion production rate down to about 55 km. The ion production rate from the bremsstrahlung produced by these electrons becomes 10 percent of the cosmic ray ion production rate at about 28 km, and the percent decreases rapidly at lower altitudes.

From the foregoing calculations and from comparisons of the measured bremsstrahlung spectra with calculations of the bremsstrahlung production from typical radiation belt electrons, we conclude that the ion production rate from bremsstrahlung produced by energetic electrons precipitating into the atmosphere is a negligible fraction of the cosmic ray ion production rate near the 300-millibar level. Thus, we conclude that bremsstrahlung is not an important factor in influencing weather patterns via the formation of cirrus clouds near the 300-millibar level as proposed by Roberts and Olson (1973*a, b*).

It is evident that bremsstrahlung radiation from precipitating electrons can at times significantly increase the ionization in the atmosphere at altitudes above about 25 km. Because this increased ionization will increase the atmospheric conductivity, bremsstrahlung radiation may be important in processes suggested by Markson (1975) for influencing the atmospheric electricity and the related development of thunderstorms. He suggests, however, that the most likely mechanism involves the variation in the conductivity over thunderstorms at somewhat lower levels, namely in the 10- to 20-km height range. Changes in the conductivity by a factor of 2 at 41.5 km due to bremsstrahlung radiation during a magnetic storm have been measured in a balloon-borne experiment (Williamson, 1973).

Bremsstrahlung radiation could also contribute to changes in the atmospheric composition as a result of the ionization produced at altitudes primarily in the 25- to 90-km range. Although a change in the atmospheric composition has been suggested as a possible mechanism to link solar activity to meteorological processes (see Roberts and Olson, 1973*b*), no generally accepted hypothesis has emerged.

If precipitating energetic electrons are found to be important in meteorological processes, some control of the precipitation rates, and thus of the meteorological processes may eventually prove to be feasible. Brice (1970; 1971*a, b*) and others (see Cornwall, 1972) have suggested that particle precipitation from the radiation belts should be feasible using cold gas injection into the magnetosphere. Also, an experiment is presently being conducted to precipitate energetic electrons from the radiation belts using VLF electromagnetic waves transmitted from Siple, Antarctica (Helliwell, 1973).

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DISCUSSION

RASOOL: What is the flux difference in cosmic rays from solar maximum to solar minimum?

JOHNSON: It is relatively small. I think it is of the order of 10 or 20 percent. In this connection, one should bear in mind that the variation of the interplanetary medium is sufficient to cause modulation of the cosmic rays of the order of a few percent; therefore, as soon as the bremsstrahlung contribution drops to a few percent, they would be of comparable magnitudes. If bremsstrahlung radiation is important as a dynamic effect, one would suspect that such importance must occur at altitudes above which the bremsstrahlung is more than a few percent of the cosmic rays.