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On the effect of solar particles over the polar upper atmosphere(*)

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Summary. — It has been reported that the abundance of nitrates in the polar region shows an 11 year periodicity which is clearly connected to solar activity. In this paper, we investigate whether or not this variation in nitrates can be explained by solar proton events (SPE) using data of the variation in galactic cosmic rays (GCR) over two solar cycles. As the result of our analysis, it would appear that SPE do not play a major role in producing the year-to-year variability in nitrate abundance in the polar region over the 11 year solar cycle. We have found that, if the short wave length ($\leq$ 300 nm) radiation from the Sun varies by $\sim$ 0.1% over the 11 year solar cycle, the variation in nitrates can be explained naturally. The explanation requires that the intensity of GCR should increase to about 3000 times its present level. It would be useful to explore whether or not our planet has been exposed to such strong fluxes of GCR as a consequence of supernova explosions in the past.

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1. – Introduction

Recently, interesting results have been obtained which suggest that cosmic rays might affect the lower cloud layer of the troposphere, causing the temperature of the Earth to vary by ±1 degree [1-5]. These types of studies fall under the general category of Space Climate, and we expect this area of research to develop greatly in the coming years. Eddy [6] had earlier pointed out that the long-term variation of the Sun must affect the climate of the Earth, which he termed the "sun-weather connection". The study of Space Climate must take advantage of the archive of data describing the past activity of the Sun, while, at the same time, investigate relevant natural phenomena related to those archival studies in near real time.

(*) The authors of this paper have agreed to not receive the proofs for correction.

One of the early examples is a study in Japan of radiocarbon (^{14}C) variations in annual tree ring growth made in the 1960's [7,8]. Since these studies involved measurements on tree rings at 11 year intervals, the year-by-year variation of ^{14}C involved in tree rings with solar activity was not measured; however, a long-term variation in the geomagnetic field was detected and an unusual increase in ^{14}C during the Maunder minimum was discovered. De Vries, in 1959, had earlier reported an increase of ^{14}C during both the Spoerer and Maunder minima [9,10]. Taking this result into account, Stuiver pointed out that the increase in ^{14}C was anti-correlated with sunspot numbers [11]. The abundance of ^{14}C over the past 11000 years has also been measured by Stuiver [12,13]. These results have been regarded as a Rosetta stone containing fundamental information in the study of radiocarbon variations.

The measurements of ^{14}C for each year between 1510 and 1954 form a particularly important component of the studies of Stuiver. However, the tree rings were only cut every ten years for the period before 1510 so no year-to-year measurements are available before that time. The group at the Solar-Terrestrial Environment Laboratory at Nagoya University has measured the variation of ^{14}C on a year-to-year basis over the period 1410–1550 with an accuracy of 0.2%. This data from this sample period, which contained the Spoerer minimum, was obtained from a Yaku cedar tree and was reported in an earlier paper [14]. Efforts will be made to extend the measurements of the annual variation of the ^{14}C abundance to the period before 1410.

The study of long-term variations with solar activity of ^{10}Be may also be very useful. It is thought that ^{10}Be reflects the level of solar activity since it is precipitated almost immediately ($<$ one year) after its creation [15,16]. Measurements of the abundance of ^{10}Be have been used in the study of long-term variations in solar activity that have taken place over the past 60000 years [17]. However, the abundance of ^{10}Be can change due to other causes. Castagnoli *et al.* had studied changes in the abundance of ^{10}Be over the past tens of thousands of years, and had discovered using paleomagnetic techniques, that around 35 ky BP there was a sudden change in ^{10}Be before an identifiable change in the geomagnetic field. Since the change in geomagnetic field did not appear to be the reason for the increase in ^{10}Be, they attributed that increase to an increase in the level of GCR [18].

It is also thought that, in addition to the cosmogenic isotopes, the abundance of the nitrate (NO_3^-) found in the ice cores of the South Pole and Greenland also reflects the level of solar activity. A Fourier analysis of the long-term variations of this nitrate abundance revealed a significant signal at an 11 year period [19-21]. More recently, a Japanese group carried out a Fourier analysis of the concentration of a nitrate in a South Pole ice core and also found a signal at a period of 11 years [22]. The cause of such a periodicity is an important puzzle as there are several possible processes that could lead to the formation of nitric oxide (NO) in the stratosphere. These are summarized below:

1) N_2O may be oxidized through biological activity such as that involving bacteria in the soil (N_2O+O $\rightarrow$ 2NO).

2) NO may be produced by global thunderstorms through the action of lightning.

3) NO may be produced through a dissociation process in the Earth's atmosphere by ultraviolet radiation from the Sun.

4) NO may be produced by an ionization process in the Earth's atmosphere due to galactic and solar cosmic rays and their secondary electrons.

5) NO may precipitate from the thermosphere and mesosphere after being produced

by bremsstrahlung radiation associated with X-rays due to the deceleration of auroral particles in the lower mesosphere [23].

6) NO may also be produced by human activities.

The processes 1), 2), and 6) seem unlikely to contribute significantly to the production of nitrates in the polar region, and the nitrate variations in the Antarctic ice cores are largely attributed to the processes 3) or 4), and 5) [21]. Researchers would like to obtain a quantitative understanding of the relative contributions of the processes 3), 4) and 5) in the production of nitrates, because it will clarify the 11 year periodicity of nitrate in the polar ice cores. In this respect, the influence on the atmosphere of unusual increases in galactic cosmic rays reported by Reid and Crutzen is well known [24]. However, these workers did not consider the possible effects of solar particles and, in our paper we will use satellite data to explore the relative importance of galactic and solar cosmic rays on the atmosphere over the polar region. Ultimately, we intend to measure the production rate of NO using accelerator beams, but in this paper we shall concentrate on the analysis using satellite data. In particular, we investigated how cosmic rays would influence the variation of the nitrate concentration by comparing the total flux contained in solar proton events (SPE) and galactic cosmic rays (GCR) and will report on that in this paper.

Both solar and galactic cosmic rays penetrate into the atmosphere and participate in the production of nitrates through an ionization process. However, the ultraviolet radiation from the Sun also affects the production of nitrates in a similar manner. It is important to understand quantitatively the relative contributions to the production of nitrates by solar ultraviolet radiation and cosmic rays. In this paper, by measuring the fluxes of solar and galactic cosmic rays over the past 22 years, we examined quantitatively whether or not solar flare particles participate in the production of nitrates.

In the next section we briefly explain the production mechanism for the nitrates. In sect. **3**, we describe the analysis procedure and the satellite data used, and report on the results of the analysis. In sect. **4** we discuss what conclusions can be reached from the results of our analysis and compare those with the results of other studies. Finally, in sect. **5** we present an interpretation of the 11 year periodicity in nitrate abundance seen in the polar ice cores.

2. – The nitrate data and its significance

It is thought that nitrates in the polar region could be generated by several possible processes that were listed above. Parker *et al.* [20] have examined some of these processes in detail, and it is worth summarizing some relevant portions of their paper here. They extracted ice cores in several places and measured the abundance of nitrate contained within them using an ultraviolet spectrophotometric analyzer. The data from two of the ice core sites (Vostok and South Pole) had several common features. One of these was that there appeared to be a relatively low abundance of nitrate during the Maunder minimum when the sunspot numbers were very low. The other common feature is that the data reflect a long-term variation although the data are spiky, consistent with short-term some irregular increases. The fact that these features were observed at such widely separated sites suggests that nitrate was deposited over an extensive portion of the polar region and therefore represents a global variability in nitrate production. A Fourier analysis of these data revealed strong peaks at periodicities of both 11 and 22 years corresponding to the solar cycle variations. Furthermore, the maximum concentration of nitrate was detected at solar maximum rather than at the minimum of the 11 year cycle.

From the above information, it is reasonable to think that nitrate abundance in the polar region is influenced by something that correlates with solar activity. The following line of logic summarizes a hypothesis which we introduce as a way in which solar activity can influence the atmosphere.

a) Recent observations suggest that the variability of ozone in the stratosphere is a result of changes in ultraviolet irradiation [25, 26].

b) Since solar flare activity reaches a peak at solar maximum, energetic particles (1–100 MeV) from enhanced numbers of SPE can penetrate into the mesosphere and perhaps even to the stratosphere contributing to the creation of nitrate through the ionization process [27].

c) Since GCR (100–1000 MeV), which can penetrate more deeply into the atmosphere than SPE, decrease with increasing solar activity, they would not play an important role in the observed variability of nitrate production although they would be responsible for some background level.

d) When an interplanetary shock produced by a coronal mass ejection (CME) is incident on the Earth's magnetosphere, magnetic field line merging and reconnection can result in enhanced fluxes of energetic ($\sim$ 1–100 keV) electrons which can precipitate into the auroral ionosphere. The lower end of this electron energy spectrum is responsible for the auroras, and the higher energy end of the spectrum produces bremsstrahlung X-rays. These X-rays might possibly penetrate to the lower mesosphere and upper stratosphere and, through an ionization process, contribute to the production of nitrates.

In this paper, we will examine the four possibilities a)–d) listed above in the context of the results obtained from our analysis of the data.

The possibility of involving the possible effects of GCR is immediately rejected for the following reason. If solar activity is strong, the strength of the interplanetary magnetic field will increase leading to an increased inability of GCR to penetrate into the inner solar system [28, 29]. For this reason nitrate abundance would be anti-correlated with GCR intensity. However, those GCR that reach Earth orbit will produce some nitrate and one effect may be suggested. If the rate of nitrate production decreases, it is possible that this decrease of nitrate production contributes to an increase in ozone concentration.

On the other hand, SPE show a positive correlation with nitrate variation. The more active the Sun becomes, the more flares will occur at the solar surface and the more SPE will affect the Earth particularly in the polar region. It is easy to imagine that increased numbers of SPE can be responsible for increased nitrate production in the upper stratosphere. Moreover, the variation of ozone concentration is positively correlated with the flux of ultraviolet radiation from the Sun and hence with solar activity (see fig. 1) [30]. It should be noted that Parker *et al.* [20] pointed out that nitrate was not necessarily created by ultraviolet radiation from the Sun since the annual increase in nitrate was observed late in the winter. However, if nitrate created in the summer were to attach to aerosols and float in the atmosphere for several months, one might consider the possibility that the nitrates will precipitate and reach the Earth when the atmospheric temperature falls in the winter of the polar region. Therefore the suggestion by Parker *et al.* [20] may not be correct, and it may indeed be necessary to consider the effects of ultraviolet radiation from the Sun. There may also be a process by which nitrate avoids being destroyed by solar ultraviolet radiation in the summer. Watanabe *et al.* [22] argued that there were two ways for nitrate to be transported from the stratosphere

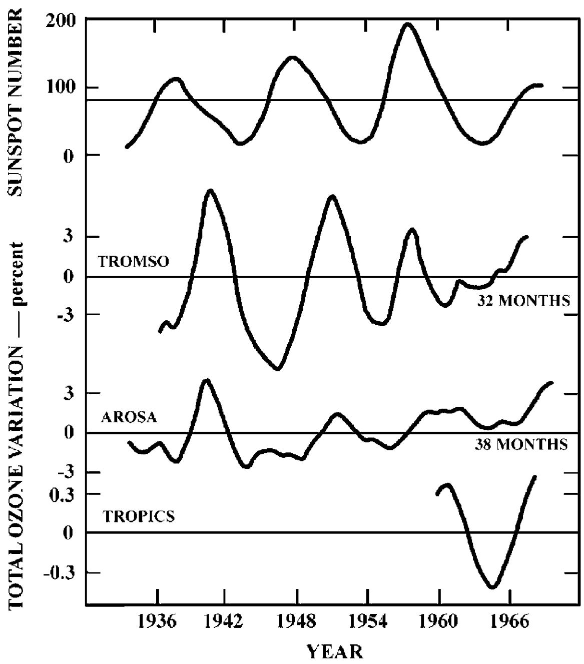

Fig. 1. – A comparison of the temporal variation in sunspot number with the smoothed percentage deviation from the linear trend of 30-month running averages of total ozone observed at Tromso, and Arosa and Tropics. The data are taken for the paper of Ruderman and Chamberlain [30].

to the troposphere. One is stratosphere-troposphere exchange of air, while the other is deposition of polar stratospheric cloud (PSC) particles which may comprise nitric acid trihydrate (NAT) ice. At present, it is not known which of these processes is the most important and that question will be addressed in the future. In this paper we will first investigate the possible effect of particles from SPE because it appears to provide the simplest and most understandable hypothesis which proposes that the 11 year cycle in nitrate abundance is caused by variations in the number of high-energy solar particles penetrating the upper stratosphere.

3. – Analysis of the satellite data

In order to understand the correlation between nitrate abundance in the polar ice cores and cosmic-ray fluxes incident on the polar atmosphere, one needs to accumulate a long-term data base of cosmic-ray fluxes. Unfortunately, no satellite has monitored the polar region for a period of time longer than one solar cycle. However, the GOES satellites located in geostationary orbit have monitored energetic proton fluxes for a rather long period of time. Since the orbital path of the GOES satellites is equatorial, the data do not directly show the flux of cosmic rays over the polar region. Here, we considered the possibility that some information transfer from the polar ionosphere to geostationary orbit might take place along magnetic field lines connecting the two locations. To obtain the fluxes of cosmic rays over the polar region, we searched for a correlation between data

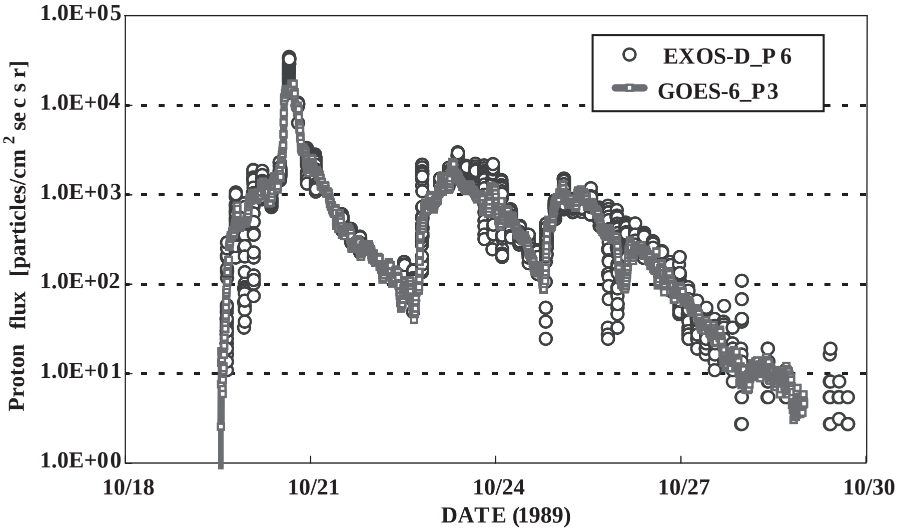

Fig. 2. – The proton intensity observed by the EXOS-D satellite and the GOES-6 satellite in the flare time on Oct. 20th, 1989. A good agreement between two data is seen.

from the GOES-6 satellite and data from the EXOS-D satellite which passed over the polar region for a relatively short period of time. The EXOS-D satellite is in polar orbit reaching geographic latitudes (ϕ) between ± 75 degrees. We have defined the proton flux over the polar region as represented by the data obtained when EXOS-D is at latitudes $\phi \geq 60$ degrees.

The data to be compared were obtained from the GOES-6 and EXOS-D satellites in 1989 between 10/19 and 10/28. Some major flares occurred during this period and several SPE were detected. The intensities of the protons detected at the two satellites were in surprisingly good agreement as seen in fig. 2. In this figure the open circles represent data from the channel P6 of the EXOS-D satellite which recorded protons in the energy range 6.6–15 MeV, while the data points connected by the black line are from the channel P3 on the GOES-6 satellite which recorded protons in the energy range 8.7–14.5 MeV. From fig. 2 it is clear that the agreement between the two satellites is quite good, and similar results were obtained for four other SPE (1990 from 05/21–06/02 shown in fig. 3, 1991 from 06/01 to 06/14 shown in fig. 4, 1992 from 05/08 to 05/15 shown in fig. 5 and 1992 from 10/30 to 11/08 shown in fig. 6).

We should point out here that the cutoff rigidity at the geostationary orbit of GOES-6 is different from that for EXOS-D whose orbit crosses the polar region at lower altitude. Since the cutoff rigidity at the location of GOES-6 (about 36000 above the equator) is approximately 50 MeV, it is impossible for solar cosmic rays with energies $\sim$10 MeV to directly reach that satellite. Therefore the flux of these protons measured by the GOES-6 satellite must have first entered the polar region and become trapped, after which they moved perpendicular to the field lines onto the flux tube where the geostationary satellite was located. This would be difficult to achieve if the Earth's magnetic field were purely dipolar, but because of its stretched geometry we believe that lower-energy protons can access the equatorial plane at geostationary orbit. This possibility has already been pointed out almost thirty years ago by Blake *et al.* [31].

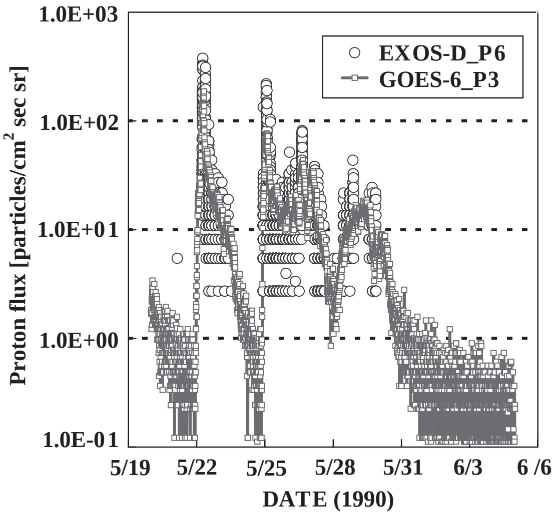

Fig. 3. – The same data as fig. 2, but for the solar flares between May 21st and June 6th of 1990.

In order to further understand the transport mechanism for protons from outside the magnetosphere to geostationary orbit via the polar region, we compared the data for 8–16 MeV protons measured by the GMS-3 geostationary spacecraft with the data for 6.6–14.8 MeV protons measured by the IMP-8 satellite in the interplanetary medium during the period 10/19–10/28 in 1989. The GMS satellites launched the same type detectors as in the GOES satellites. These data are plotted in fig. 7 together with the data obtained by GOES-6 and EXOS-D. The fluxes of energetic protons detected by the four satellites located in very different places show similar behavior at the time of large

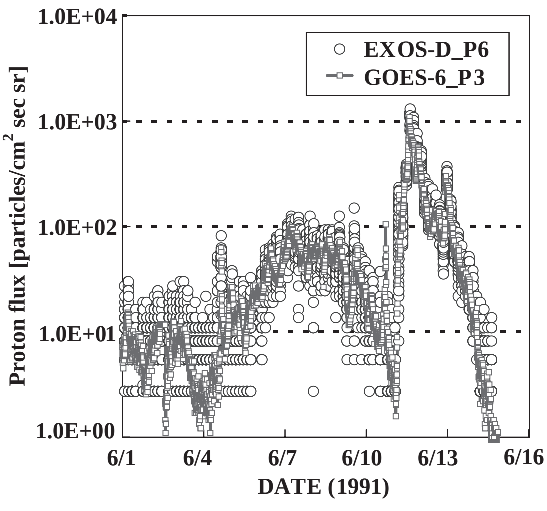

Fig. 4. – The same data as fig. 2, but for the solar flares between June 1st and 15th of 1991.

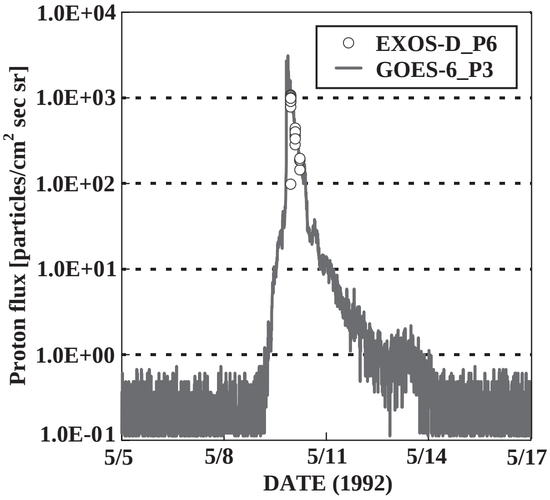

Fig. 5. – The same data as fig. 2, but for the solar flares between May 5th and 17th of 1992.

solar flares. It is astonishing to see that even the absolute values of the fluxes agree very well with one another.

Since a good phenomenological correlation exists between the energetic proton fluxes at GOES-6 and EXOS-D, we shall use the data from GOES-6 located in the equatorial plane as a proxy for the global flux of protons which enter the polar region of the Earth at the time of a solar flare. Henceforth, we shall continue our discussion of the flux of cosmic rays in the polar region using the data of GOES-6 as a proxy.

The data used for our analysis comprises 5-minute average values of the proton flux

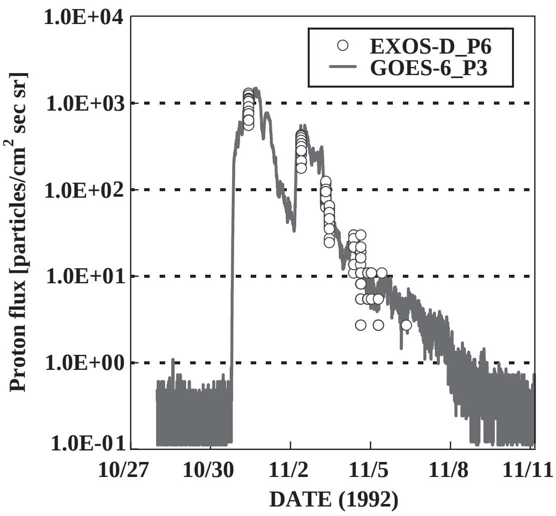

Fig. 6. – The same data as fig. 2, but for the solar flares between Oct. 27th and Nov. 10th of 1992.

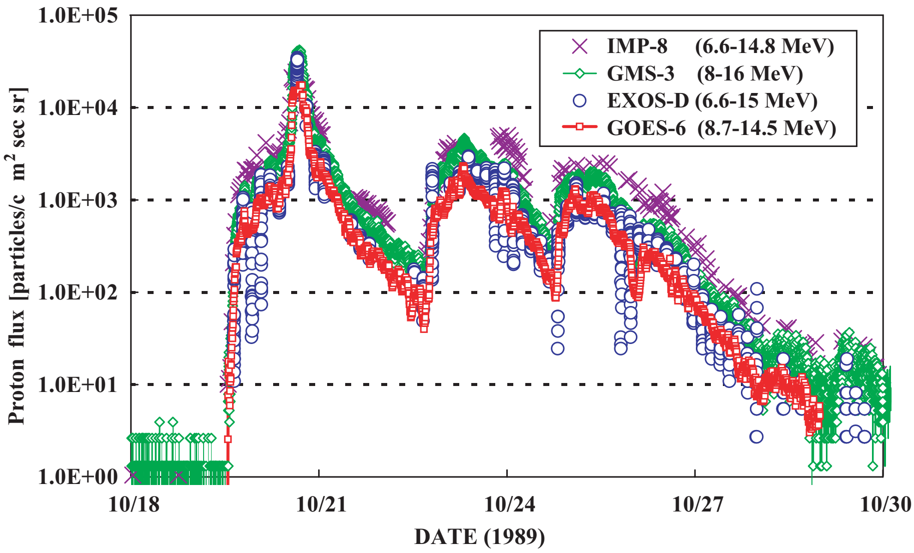

Fig. 7. – The proton intensities obtained by four satellites which were located in a polar orbit (EXOS-D), at geostationary orbit (GOES-6, GMS-3) and in interplanetary space (IMP-8) are shown. It is surprising to see that the data obtained at different positions in association with solar flare of Oct. 20th, 1989 are so similar, even in the absolute value.

obtained by GOES-6 from 01/01 in 1978 to 12/31 in 2000. We first defined the background intensity at normal times as the flux of GCR. The differential energy spectrum obtained using the P2-P7 channels of GOES-6 were then integrated over one year (P2: 4.2–8.7, P3: 8.7–14.5, P4: 15–44, P5: 39–82, P6: 84–200, P7: 110–500 MeV). Then the total year-by-year flux of GCR at the location of GOES-6 was calculated, which we henceforth call the flux of GCR. Data obtained during times when solar flares took place or Forbush decreases were detected were discarded in this method for obtaining the background intensity.

Next, the flux of SPE protons produced by solar flares was defined as the increase in flux above the background level when the flux measured by the P2 channel at GOES-6 was greater than a factor of 2 above the normal background intensity. Even if the threshold were decreased to 1.5 above the normal background intensity, the total amount of ionization does not change. When such a situation arose for a period of greater than one hour, this was regarded as the signature of a solar flare. We then integrated the flux from each channel (P2–P7) over the time period when the above criterion was met. Each spectrum was used to obtain the energy spectrum for the total flux associated with SPE for each year. In the case of events which occurred between 1978 and 1985, the data set from the GMS satellite alluded to earlier was used instead of the GOES-6 data. The GMS satellites launched the same type detectors as in the GOES satellites.

The result of the analysis is shown in fig. 8. We should like to point out that the production rate of nitrate by cosmic rays is proportional to the total energy deposited in the upper atmosphere, and not to the number flux. Cosmic rays with energies >10 MeV can penetrate to the stratosphere. The GOES-6 satellite can monitor the energy range from 4.2–500 MeV (channels P2–P7), and we have assumed that the intensity of GCR extends to higher energies following a power law. (The contribution beyond 1 GeV is only

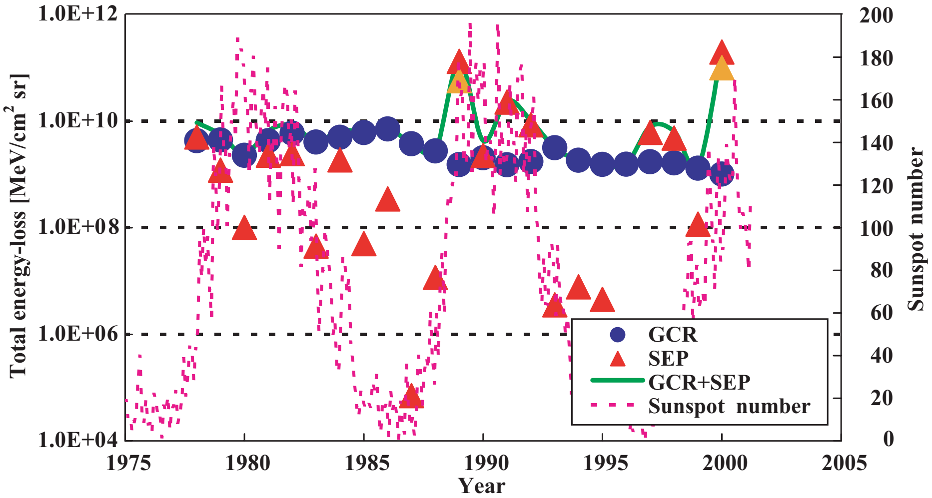

Fig. 8. – The total energy-loss of SPE and GCR in the stratosphere is plotted for each year between 1978 and 2000. The dotted line shows the sunspot number. During solar cycle 22, the intensity of SPE dominates that that of GCR. Even if we take out the large events on Oct. 20th, 1989 and July 14th, 2000 (orange triangle), the trend does not change so much. In contrast, the intensity of GCR dominates the flux of SPE in the solar cycle 21 (1976-1986).

10% of the total flux.) The contribution of cosmic rays with energies higher than 1 GeV to the ionization loss in the stratosphere (1–400 g/cm^2) must be around 50% of the total energy deposited. Hence, it is the total energy of the cosmic rays deposited in the upper atmosphere that relates to the production of nitrate in the stratosphere and not the total number flux of cosmic rays. Figure 8 shows the total energy deposited by SPE and GCR in the stratosphere, together with the sunspot number. It can be seen from this figure that, during solar cycle 22, the energy loss of SPE was up to two orders of magnitude larger than that of the GCR. On the other hand, during the maximum of solar cycle 21, the energy deposited by GCR and SPE were of the same order of magnitude with the energy associated with the GCR being marginally larger.

4. – Discussion

Assuming that the energy spectrum beyond 500 MeV (the upper end of the range covered by GOES-6) has a power law form, we have reached the following conclusions based on our data analysis:

1) During solar cycle 22, the influence of SPE on the stratosphere was larger than that of GCR in terms of the production of ion pairs.

2) In contrast, during solar cycle 21 the number of ion pairs produced by SPE was of the same order as the number produced by GCR, or even marginally less. A similar result was obtained recently by Shea *et al.* [32, 33]. They calculated the fluence of SPE and GCR and pointed out that, particularly during solar cycle 22, the fluence of SPE was large compared to that for solar cycles 20 and 21. Their results and those from our study are consistent with one another in that respect.

3) Based on the above information, it is hard to believe that the 11 year variation in

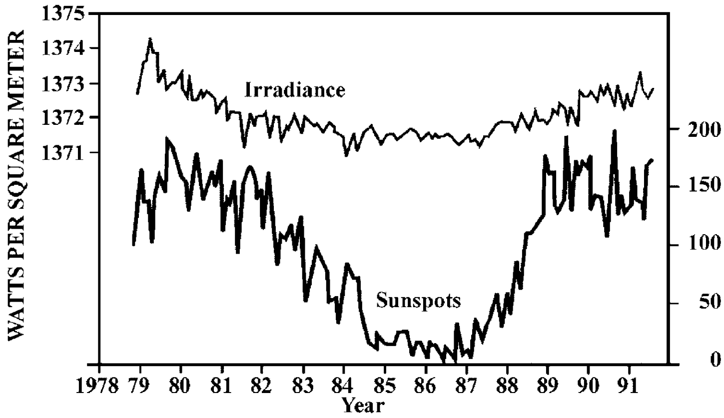

Fig. 9. – The luminosity of the Sun and the sunspot number are plotted. The upper curve shows the monthly mean irradiance of the Sun, recorded by the NASA Nimbus 7 spacecraft. A ∼0.1% variation in irradiance can be seen over the 11 year period. The lower curve shows the sunspot number (after Parker [34]).

nitrate might be produced by solar energetic particles.

4) We now consider the possible role of auroral particles, which are primarily electrons in the energy range of 1–100 keV with typical energies of a few keV. Electrons in this energy range would cause the production of bremsstrahlung X-rays of 0.5–1 keV. However, the attenuation length of ~ 1 keV X-rays is only 10^{-3} g/cm^2 and even the X-rays produced by the highest-energy auroral particles (~ 100 keV) will be stopped by an atmosphere of 1 g/cm^2. This corresponds to an altitude of ~ 50 km above sea level, corresponding to the boundary between the mesosphere and stratosphere, so these X-rays would be unlikely to ionize the nitrogen and oxygen molecules of the upper stratosphere. Nitric oxide created in the lower mesosphere cannot be transported into the stratosphere by any known mechanism. Therefore, despite the fact that the intensity of auroral particle flux is positively correlated with solar activity, it is hard to imagine them as responsible for the production of nitrate in the stratosphere without the existence of some, as yet, undefined transport mechanism.

5) We now investigate the possible importance of GCR by calculating their total energy, noting that energies in excess of about 1 GeV are required if they are to penetrate to the lower stratosphere. It is estimated that such cosmic rays produce $\sim 10^7$ ion pairs in the stratosphere and, assuming a peak in energy near ~ 1 GeV, GCR could produce about 10^{12}/cm^2 ion pairs per day which can contribute to the formation of nitric oxide.

The estimate above and the production rate of ion pairs driven by the W-value of the air (35 eV) are approximately the same: 1×10^9 eV/35 eV$\times8.6\times10^4 = 2.5\times10^{12}$ /cm^2/day as shown in fig. 8. Of course, GCR will not contribute to the solar cycle variation of nitrate abundance since it is inversely correlated with GCR. However, it is interesting to note that the processes 4) and 5) have nearly the same ionization capability.

6) The solar constant has been assumed to be a stable parameter for a very long time. It would seem, on the surface, unlikely that its value would be affected by the solar cycle activity since the Planck energy spectrum of the Sun is controlled mainly by the deep interior processes. In fact, the effect by the observation is less equal than

0.1% [34, 35]. Observations suggest that solar luminosity varies at about the 0.05% level with solar activity, which is about the expected accuracy of the measurements themselves (cf. fig. 9) [34, 35]. It has been reported that solar ultraviolet radiation changes at about the 5% level with solar cycle activity, however since these measurements were made through the limb of the Earth, it is hard to believe that there is not some contamination due to chemical processes in the mesosphere. Therefore, for the time being, it is reasonable to set a limit of the variability of solar ultraviolet light to between 0.1% and 7% at 240 nm [25].

We now calculate how much nitrate is created through the action of solar ultraviolet radiation assuming that the photon energy can be expressed as hν. This permits us to obtain the total number of photons (N_ν). The radiation between 190 nm and 240 nm is estimated as about 3×10^{-5} W/cm^2. If the energy of one photon is about 10^{-18} joule, no less than 3×10^{13} photons /cm^2/s will be incident on the upper atmosphere in the polar region. Note that the attenuation length for UV photons in the upper atmosphere is about 3.3 g/cm^2 at 240 nm.

Consider that one photon collides with an oxygen molecule to make two oxygen atoms. Then the number of oxygen molecules dissociated would be about 3×10^6 times larger than the number of ion pairs produced by cosmic rays. Furthermore, if we assume that the 11 year solar cycle produces a variation of 0.1% in ultraviolet radiation, this would suggest that the variation in nitrate abundance produced by that ultraviolet radiation is 3000 times larger than that produced by GCR. If the intensity of SPE is more than 3000 times that of GCR, our estimate shows that the influence of SPE is of the same order as that of solar ultraviolet radiation in terms of nitrate production. It is very important to make long-term measurements of solar ultraviolet radiation between 190 nm and 240 nm to see whether or not it changes by 0.1% or greater over an 11 year solar cycle.

We now turn our attention to a very important event in the recent past, namely a large-scale nuclear test performed in the atmosphere in 1962. It has been estimated that 4×10^{31} NO molecules were produced in the atmosphere by that one megaton explosion [30, 36, 37]. When distributed around the world, this corresponds to 10^{15} NO molecules per cm^2. This is about 3000 times what is produced by GCR in a year, and surprisingly about the same amount that would be produced by a 0.1% variation in ultraviolet light from the Sun.

We can now conclude that if the intensities of GCR and SPE are what are normally expected, they will not have a significant effect on the stratosphere. If the intensity of cosmic rays increased by a factor of 3000, one should be able to detect an increase in nitrate and a decrease in ozone abundance. Reid *et al.* [24] have estimated that an increase in cosmic ray intensity by a factor of 1000 would decrease the abundance of ozone by a factor of 10. Our estimate suggests that an increase in cosmic ray intensity by a factor of 3000 would lead to a 6% decline in ozone abundance. This difference stems from the fact that we assume that only ultraviolet radiations with wavelengths of 240 nm or less are involved in the dissociation of oxygen molecules.

7) We would now like to address the question of the unusual increase in nitrates observed in the year of the Carrington flare [38-40]. It is worth pointing out that a flux of solar particles in a year an order of magnitude higher than the present GCR flux could be generated by previous solar flares. It would probably be unrealistic to believe that gigantic solar flares could produce 3000 times the energy of any previously observed flare. However, for a white light flare, if the ultraviolet radiation equivalent worth the flux in a year also increased by about 1% and continued for a day it would be quite possible to

detect an increase in nitrate abundance. We believe that the nitrate spike detected at the time of the Carrington flare must have been produced by such an increase in ultraviolet radiation.

8) While it is interesting that the observed solar cycle variation in nitrate abundance could be produced by a 0.1% increase in solar ultraviolet radiation, it is astonishing that the amount of nitrate produced by the 1 megaton nuclear test explosion in the atmosphere could produce a similar increase. Based on our considerations, it is reasonable to suggest that the variation of ultraviolet radiation in the 240 nm wavelength range could vary by about 0.1% over the 11 year solar cycle period.

9) We can now go back to ask why the global weather was so cold during the time of the Maunder minimum. In that case, even if the solar luminosity did change by about 0.1% [34, 35], the Earth's climate did not follow the 11 year solar cycle. Therefore the cold period during the Maunder minimum cannot be explained only by a 0.1% decrease in ultraviolet radiation from the Sun. It is necessary to suggest a new hypothesis such as the one made by Svensmark [1, 2] or it may be that the cold climate was associated with something like an increase in the odd oxides of nitrogen and a decrease in ozone over a long period of time.

5. – Conclusion

In this paper we have investigated a correlation between the amount of nitrate and the total energy loss of cosmic rays in the polar region. In particular, we analyzed the intensities of SPE and GCR over the polar region over the years of solar cycles 21 and 22 using satellite data. From our analysis, the total number of ion pairs created in the stratosphere by SPE was of the same order of magnitude or less than would be expected from GCR. However, for solar cycle 22, it turned out that SPE were more than an order of magnitude more effective than GCR, while for solar cycle 21 they did not play a significant role.

The 11 year periodicity in the abundance of nitrate observed over the lengthy interval between 1920 and 1980 [22] is difficult to explain on the basis of SPE alone. If the amount of solar ultraviolet radiation below about 240 nm changes by about 0.1% over the 11 year cycle, this might be able to explain the variation in nitrate abundance. It would be both interesting and important to monitor the output of the Sun at wavelengths below ~ 350 nm for a long period of time so long as the light did not pass through the limb of the Earth before detection.

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