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THE SOLAR DAILY VARIATION OF THE COSMIC RAY INTENSITY

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ABSTRACT

Some recent measurements of the solar daily variation for cosmic rays incident from the east and west directions at 45° to the vertical in London are described. The results do not agree with those to be expected if the variation was due to a non-isotropic flux of primary particles entering the earth's magnetic field. This result is discussed in relation to other evidence and it is concluded that the daily variation is probably due to a modulation of the primary cosmic ray intensity in the earth's magnetic field.

1. INTRODUCTION

It is generally believed that the solar daily variation of the cosmic ray intensity is due to a variation of the primary radiation incident on the earth's atmosphere, this intensity variation being produced in some way which is at present not understood. Observations to date have been made at sea-level using ionization chambers, counter telescopes and neutron monitors. Counter telescopes have the advantage that they make it possible to measure the variation for different directions of incidence at the earth's surface whereas ionization chambers and neutron monitors accept radiation within a solid angle which is limited only by atmospheric absorption. Since counter telescopes record primarily either the μ-meson flux or the combined μ-meson and electron components, the intensity observed at sea-level is dependent on atmospheric temperature and pressure. In relating the intensity changes observed at sea-level to changes in the primary intensity, it is therefore necessary to correct for these meteorological variables. In investigations of the solar daily variation it is possible to make an adequate correction for the variation in barometric pressure but in order to correct for temperature it is necessary to know the daily variation in temperature throughout the atmosphere. At present the daily variation in atmospheric temperature is uncertain because of the

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limitation, in particular the susceptibility to radiation errors, of the instruments used for routine measurements.

In the absence of accurate information about the daily variation in atmospheric temperature, attempts have been made to separate the part of the cosmic ray variation due to atmospheric temperature from that due to variations of the primary intensity by using directional telescopes. These telescopes have been so arranged that they record radiation arriving from quite different parts of the sky but respond in an identical manner to variations in intensity due to atmospheric temperature and pressure changes (Elliot and Dolbear [1], Malmfors [2]). Measurements of this kind together with observations on the nucleonic component, which is not temperature sensitive, have established beyond doubt that the daily variation is largely due to a variation in primary intensity incident on the atmosphere. This variation has been generally attributed to an anisotropic primary intensity entering the earth's magnetic field.

In order to determine the true direction of anisotropy from the observed daily variation, it is necessary to know the deflexion experienced by the primary particles in passing through the earth's magnetic field. The trajectories of cosmic ray particles in the earth's field have been investigated by Brunberg and Dattner [3] by means of scale model experiments. Using the data on the trajectories obtained in this way, Brunberg and Dattner [4] have shown that it is possible to account for the daily variation observed with counter telescopes pointing in the north and south directions at 30° to the vertical if it is assumed that the mean energy of the primary radiation responsible for the variation lies in the region 2 to 4×10^{10} eV. With this assumption, an anisotropy of the primary radiation with a direction lying near the plane of the ecliptic would produce a daily variation of nearly the same amplitude for the north and south directions but with a phase difference of about 2 hr as was indeed observed in 1948 and 1949 (Malmfors [2], Elliot and Dolbear [1]).

Brunberg and Dattner's data on trajectories show that at latitude 50° primary particles of energy 3×10^{10} eV, which have initial directions nearly parallel to the earth's magnetic axis, are deflected in the earth's field so as to arrive from the west at 45° to the vertical. Those with the same energy but with initial directions in the geomagnetic plane, arrive from the east at 45° to the vertical. Consequently, if we point a counter telescope in the east direction at 45° to the vertical it should record the daily variation due to anisotropy of the primaries plus any variation of atmospheric origin since, as the earth rotates, this telescope will scan a strip round the celestial sphere. A telescope pointing at 45° to the west, however, collects radiation from very nearly the same direction through the day and should therefore show only the atmospheric part of the variation.

Observations have been made over a period of one year in London using two counter telescopes arranged in this way and the results are described below.

2. EXPERIMENTAL ARRANGEMENT

Each counter telescope consisted of three trays of counters 60 × 60 cm in coincidence, the extreme trays being separated by 140 cm. The trays were mounted in metal frameworks so that the axes of the telescopes pointed east and west at 45° to the vertical. No absorber was used and the counting rate of each counter set was ~ 15,000 per hr. The apparatus was in operation

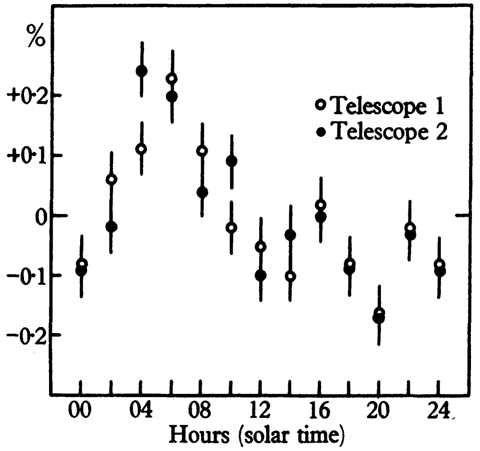

Fig. 1. Bi-hourly departures from the mean for the two telescopes averaged over the period of the measurements.

from May 1954 to April 1955 and during this period the two telescopes were interchanged from time to time in order to eliminate any systematic instrumental difference which might have influenced the daily variation measured by the two telescopes.

As a check on the performance of the equipment, the daily variation data have been added together for each of the two telescopes over the period during which the observations were made. Each telescope having spent the same length of time looking east and west, any instrumental difference would be revealed as a difference between the average daily variation, measured by the two counter sets. Fig. 1 shows the bi-hourly departures from the mean for each of the two telescopes. It can be seen

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that there is no obvious systematic difference and this is confirmed by Fig. 2 in which the first harmonics for the two sets of data are plotted on a harmonic dial. The harmonic coefficients agree to within the statistical error and we therefore conclude that any systematic difference due to instrumental defects is so small that it can be neglected.

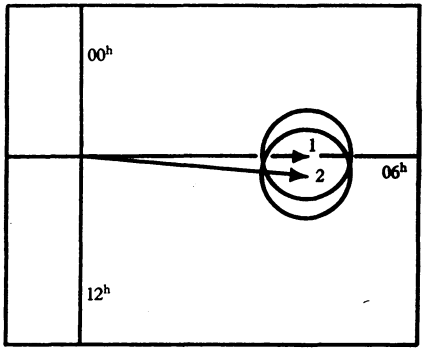

Fig. 2. Data from Fig. 1 plotted on a harmonic dial showing the absence of any systematic difference between the two telescopes.

3. THE DAILY VARIATION FOR THE EAST AND WEST DIRECTIONS

Fig. 3 shows the mean daily variation for the east and west directions for the period April 1954 to April 1955. The data have been corrected for the variation in barometric pressure using a coefficient of 2·7 % per cm Hg. This coefficient was deduced from the day-to-day changes in the rates of the two telescopes due to variations in pressure. The daily variation in barometric pressure in these latitudes is small and the correction does not greatly change the appearance of the curves. Fig. 4 shows the first and second harmonics of these curves plotted on harmonic dials which show that the amplitude of the 12-hr waves are not statistically significant. The amplitude of the 24-hr wave in the west direction is seen to be about three times as great as that for the east direction.

4. DISCUSSION

It is extremely difficult to reconcile this result with the view that the daily variation is produced by an anisotropy of the primary radiation existing at large distances from the earth since, as pointed out in section 2, such an

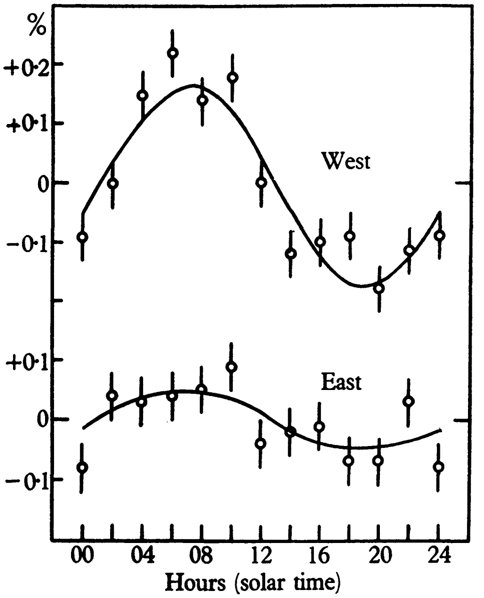

Fig. 3. The mean solar daily variations for the east and west directions after correction for barometric pressure, April 1954 to April 1955 inclusive.

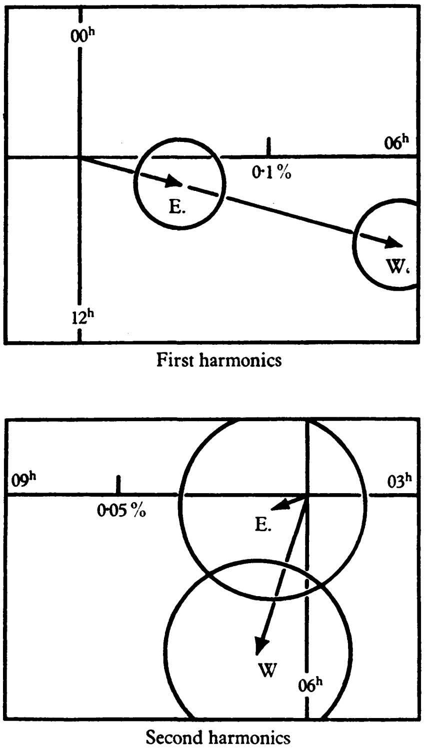

Fig. 4. Harmonic dials showing the mean 24-hr and 12-hour waves for the east and west directions after correction for barometric pressure.

anisotropy would lead to a larger variation in the east direction than in the west. The basic assumptions involved in this argument are:

(*a*) that the average energy of the primaries responsible for the variation is in the range 2×10^{10} eV to 4×10^{10} eV, as deduced by Brunberg and Dattner [4] from the observed variation in the north and south directions in 1948, and

(*b*) that the direction of greatest anisotropy lies in or near the plane of the ecliptic.

The measurements in the north and south directions were made during 1948 and it is possible that the mean energy of the primary radiation responsible for the daily variation has changed since that time. It is certainly true that the amplitude of the variation has been decreased and that the phase has also changed (Thambyahpillai and Elliot [5], Sarabhai and Kane [6]). This could be interpreted as a decrease in average energy of the primaries producing the variation and if one supposes that the energy has decreased to a value of $1 \cdot 5 \times 10^{10}$ eV or less, the trajectories for primaries incident on the earth from either east or west have initial directions which lie in or near the equatorial plane. Under these circumstances both telescopes would be exploring the same strip of sky and should therefore show the same daily variation. It does not seem possible, however, even on this basis, to account for a larger variation from the west than from the east unless one supposes the mean energy to have decreased to a value well below 10^{10} eV when such particles are unable to reach the earth from an easterly direction because of the earth's shadow cone. It then becomes impossible to account for the existence of a daily variation in the equatorial region since the primaries responsible would be unable to reach the earth's equator from any direction.

Turning now to assumption (*b*), it is possible to envisage some direction of anisotropy which, lying at an angle of 70 or 80° to the plane of the ecliptic, might produce a larger variation on the west pointing telescope than the east. This again leads to difficulty, however, in accounting for the existence of an appreciable daily variation at the equator since the amplitude of the observed variation would be smallest at the equator and increase with increasing latitude. In fact the reverse applies (Elliot [7]).

In summarizing, we may conclude that it is extremely difficult to envisage a state of affairs which enables us to account for the observed variation in the east and west directions in terms of an anisotropy which exists at such a distance from the earth that the asymptotic directions of the primary particles are relevant.

Apart from these results for the east–west directions, there are other

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characteristics of the variation which are equally difficult to understand on this interpretation and these will now be briefly discussed under (*a*) and (*b*).

(*a*) It is known from comparison of the latitude variations (Fonger [8]) that the nucleonic component at sea-level arises from primaries of lower average energy than those which produce the bulk of the μ-mesons and electrons at sea-level. Because of this difference in primary energy, the deflexion in azimuth of the primaries which produce the nucleonic component must be greater than that for the primaries of the ionizing component. The sense of this deflexion is such that a given direction of anisotropy would produce a daily variation in the nucleon flux with an earlier phase than that for the ionizing component. Simultaneous measurements of the daily variation for the ionizing component and for the nucleonic component were made in Manchester during the period June 1952 to May 1954. During the two periods June 1952 to May 1953 and June 1953 to May 1954, the times of maximum for the nucleon variations were 1330^h and 1300^h respectively, compared with 1040^h and 0840^h for the ionizing component. During both these periods the phase of the daily variation for the ionizing component was in advance of that for the nucleons which is the contrary of what would be expected from consideration of the primary energies involved.

(*b*) During the period of the present measurements in the east and west directions, simultaneous measurements in the vertical direction in London revealed some remarkable changes in phase of the daily variation for vertical particles (Possener and Van Heerden [9]). During the period June to November 1954 the time of maximum intensity was 0300^h whereas from December 1954 to March 1955 it was 1000^h. No comparable change in phase was observed in either east or west directions and if this phase change represented a genuine change in direction of the anisotropy at this time, it is hardly conceivable that it should not, at the same time, have appeared in the east–west data.

The discussion above leads us to the conclusion that the interpretation of the cosmic ray daily variation as the result of a non-isotropic primary flux entering the earth's magnetic field may well be incorrect. Directional telescope measurements, however, show that the amplitude and phase of the daily variation depend on the direction of observation, so the variation cannot originate in the atmosphere. If these two statements are to be reconciled, it seems that the intensity modulation, which we observe as a solar daily variation, must take place in the earth's magnetic field.

5. CONCLUSION

The results of measurements in the east and west directions together with other known characteristics of the daily variation lead to the conclusion that the daily variation is not due to an anisotropic primary flux entering the earth's magnetic field but is most probably produced by modulation of the primary intensity within the region occupied by the field.

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Discussion on Papers 39, 40 and 41

Singer: At the Mexico conference I suggested that the earth's magnetic field itself might be responsible for the anisotropy. It seems to me that when the earth moves in the interplanetary gas the magnetic field will be deformed by the streaming gas and therefore the field should become anisotropic in longitude. This could produce some anisotropy in cosmic radiation.

Further, as Sarabhai pointed out, the diurnal variation at Kodaikanal is different from other places such as Freiburg and Ahmedabad. Could this be accounted for by a different low energy cut-off? How does it fit in with Elliot's results?

Sarabhai: I do not think that the mean primary energy for the intensity measured at Kodaikanal differs adequately from the mean energy for the intensity at Trivandrum or Ahmedabad to explain the absence of the effect of Kodaikanal. We do not at the present moment see why Kodaikanal behaves differently from the other stations.

Alfvén: In reply to Elliot I should like to say that I cannot see why two different energies should have the same diurnal effect. The anisotropy of cosmic radiation may be a product of the influence of the interplanetary electric and magnetic fields on cosmic radiation but I think it is not in order to assume that low-energy particles and high-energy particles should react in the same way to this field. It depends very much on the radius of curvature, etc. Further, suppose that you have an interplanetary magnetic field somewhat like that given in Fig. 5*a*. In one case you point the telescope in the direction *A* and in another case you point it in the direction B and it is not necessary at all to believe that the amplitudes measured in these different directions should differ very much. I do not think that at present this is an argument against the assumption of an interplanetary field.

Dr Sarabhai has pointed out that there are maxima occurring at two different times and the conclusion from that was that it is not worth while to take the first harmonic of the variation. I think that although this is a very interesting point of view it does not at all reduce the importance of a first harmonic. If we go from the problem of interplanetary winds to that of terrestrial winds, for example, we may have today here in Sweden a wind from the north or the east.

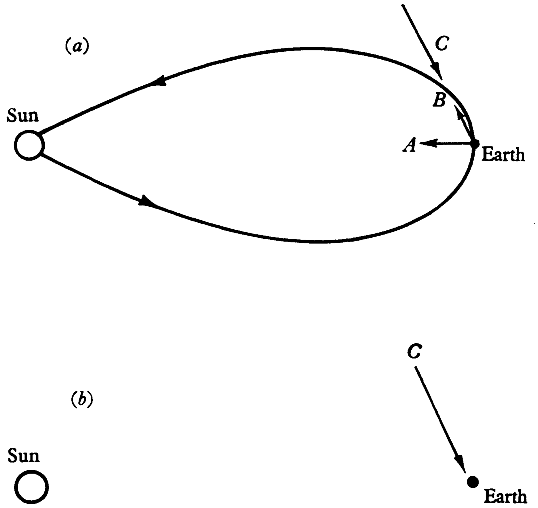

Fig. 5 (*a*). A model of the interplanetary magnetic field in a plane perpendicular to the equatorial plane. (*b*) The direction of the general dift of 10^{10} eV protons in the equatorial plane.

But if you take the average of the whole year you get a south-west wind and if you make the same analysis for Greenland you get a north-east wind. In the same way, even if you have changing directions of the anisotropy, the average means something and there could be drawn important conclusions from it.

Elliot: I want to make two objections to what Alfvén said. First, the picture (Fig. 5*a*) is slightly misleading because in the picture the lines of force are crossing the frame of the ecliptic at right-angles. This means that your lines of force are pointing to a fixed position on the celestial sphere. If one has, e.g. a flow of particles down the lines of force, then one could not see the solar daily variation but the sidereal daily variation.

The second point is that the arrow which points out into the plane of the ecliptic (A in Fig. 5*a*) would then indicate that Sarabhai near the equator would not see any daily variation at all.

Sarabhai: In my mind there is an important difference between the analogy of winds and cosmic radiation. I was trying to suggest that, in the case of anisotropy, there are perhaps two different preferred directions and there is no physical reality to an intermediate anisotropy. If you make a harmonic analysis, you will get all the intermediate values of the first harmonic depending on the frequency of occurrence of anisotropy in each of the two preferred directions. Therefore the physical reality to be attached to the movement of the first harmonic is not clear. I cannot say that the first harmonic has no physical reality, but you have also to take account of the second harmonic.

As to the work of Dr Elliot I think a rather crucial point is raised. However, one difficulty in experiments at northern latitudes is, as Brunberg and Dattner have shown, that the corresponding orbits are somewhat complicated. We cannot reconcile the results of east and west observations at the equator, unless we have an anisotropy which becomes negligible below a certain minimum energy.

Regarding the neutron observation that Dr Elliot reported I would like to have from him the following information. What is the relative amplitude in these two cases measured in London, and what is the aperture of the telescope?

Elliot: The relative amplitude was about two. The amplitude of nucleonic variations was about twice that of the ionizing component. A fairly wide aperture was used in the telescope.

Sarabhai: Then I do not think that the two experiments are quite comparable. As I pointed out before there exist components which are fairly well collimated.

Elliot: I do not think that it matters if you choose a wide or a narrow angle. If you choose a wide one the amplitude will be reduced but you will still see the same maximum in intensity. Brunberg and Dattner's curves are quite regular.

Sarabhai: I am not sure that you are right. Taking, e.g. the measuring telescopes pointing east and west, these will not point in the same direction in the sky and you may miss some of the collimated components by averaging over wide angles.

Gold: The enhanced diurnal variation periods earlier this year would seem to argue against any local modulation mechanism. There were groups of days with clear 27-day recurrence tendency, but no detectable relation with magnetic disturbances. For these days the variation appears to be actually due to an addition to the number of particles, not a symmetrical modulation.

Simpson: I wish to ask Dr Elliot a question for information on his excellent results. The 24-hour variations during 1954 show dramatic shifts in time of maximum from one month to the next. How was this taken into account in your analysis?

Elliot: It was taken into account. The point is that precisely the same days were taken for both types of observations, so even if one has shifts in these the relative shift would still be observed and so there should be no bias introduced.

Ehmert: When we first found these abnormal diurnal variations in the years 1950 and 1951 amplitudes of 3% were observed. Often some consecutive days showed the effect with decreasing amplitude and a slight shifting of the phase from day to day. Often these days also showed a small general decrease of intensity. For large amplitudes the curves sometimes exhibited kinks that occurred in Germany as well as 8–10 hr earlier in Japan. This seems to point to an external influence.

Block: Dr Elliot said that it would be difficult to explain the times of maximum intensity of the cosmic ray components by an anisotropy of the primary cosmic radiation. Also if the magnetic field lines of Alfvén's interplanetary field make a right-angle with the equatorial plane no daily variation of the neutron component would result at the equator.

This is not so because the earth is not generally situated exactly in the equatorial plane as in Fig. 5*a*. I have recently made some calculations of cosmic ray orbits in this field. They show that 10^9 eV protons (giving the neutron component) move very nearly along the field lines, so there should be a maximum

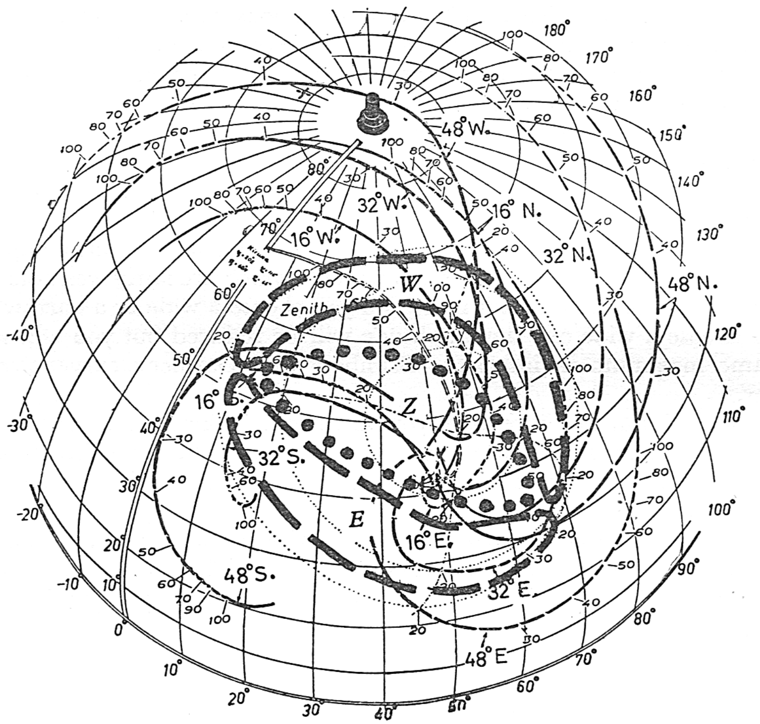

Fig. 6. The three surfaces laid out on the globe for Kiruna by Brunberg (*Tellus*, **8**, 224, 1956) refer to counter telescopes mounted in the directions 30° E., *Z*, and 30° W. with angular openings of approximately 22° in the east-west direction and 90° in the north-south direction.

at about noon also in the equatorial regions of the earth in fairly good agreement with the time given by Dr Elliot. On the other hand, 10^{10} eV protons show up a general drift in the equatorial plane in the direction indicated by the arrow *C* in Fig. 5*b*. This agrees also very well with the time of maximum for this component given by Dr Elliot.

Sandström: I should like to make some remarks on the direction of the primary particles registered by telescopes at a certain zenith angle. Preparations for an experiment of a similar nature to that of Dr Elliot's has induced me to look into this question. There is a marked difference between the influence of a change of energy of the primary particles on the registrations by a telescope directed to a certain zenith angle as compared to one directed to zenith. This is apparent from Brunberg's globes as shown by Fig. 6 which refers to a telescope arrangement in Kiruna. The central surface (dotted boundary) shows the directions in which primary particles arrive when the telescope is directed to the zenith. The surface bounded by a dashed line and indicated by E corresponds to a telescope directed to the east with zenith angle 30°, and the surface indicated by W to another telescope directed to the west with the same zenith angle. If the energy of the primary changes the zenith surface only widens and the average direction will remain the same. The two surfaces representing the directions of the primaries entering the telescopes making zenith angles of 30° will move outwards and sideways thus creating a difference in time correction (which can be mistaken for a component of daily variation of intensity). For the telescopes in the north–south directions this dependence on the energy of the primaries is small as compared to the east–west directions, as long as we keep to high and medium latitudes. Thus, measurements in the east–west directions are complicated. To take care of that difficulty measurements ought to be made at several latitudes with one direction of measurement common.

Incidentally a set of telescopes in Kiruna is now in the east–west direction for a short time. There was no difference at all between the amplitudes in the two directions (averaged over the year 1954).

Elliot: The proposal of Dr Sandström is certainly an excellent one.