REM MEASUREMENTS ABOARD MIR DURING 1995

P. Bühler[1], L. Desorgher[1], A. Zehnder[1], E. Daly[2], and L. Adams[2]

[1] *Paul Scherrer Institute, CH–5232 Villigen PSI, Switzerland*
[2] *ESA/ESTEC, NL–2200 AG Noordwijk, The Netherlands*

Reference: *Adv. Space Res.*, **21**, 1645-1649 (1998)

ABSTRACT

Measurements of the South Atlantic Anomaly (SAA) made with the Radiation Environment Monitor (REM) aboard Mir from November 1994 to February 1996 are presented. During this period an increase of the SAA radiation by ≈25% is observed, which coincides with a lowering of the radio solar flux. Radio solar flux is one of the parameters controlling the earth's atmospheric distribution and with it the absorption of inner radiation belt protons forming the SAA. Due to the altitude gradient of the atmospheric density, the proton fluxes in the SAA are anisotropic (loss cone, east–west effect). The measured distribution can be accounted for by basic models.

INTRODUCTION

In the guiding center approximation the motion of charged particles trapped in the earth's magnetic field is described by the cyclotron motion around the field lines, the bouncing between the mirror points, and a drift around the earth. The shells which these combined motions trace out are labeled with the geomagnetic radial coordinate L (in units of earth radii, R_{E}) and are referred to as L–shells. At the mirror points the particles dip deepest into the atmosphere, where they can interact with the ambient atoms and molecules and become lost. The altitude of the mirror points depends not only on L–shell value and pitch angle, but also on geographic position, as the dipole axis of the earth's magnetic field is tilted and shifted relative to the earth's rotation axis. For inner belt particles at L–shell values between 1 and 2.5 R_{E} the magnetic field configuration is such that the mirror points are lowest in a region centered on the east cost of Brasil, in the so–called South Atlantic Anomaly or SAA. This is thus the area where the particles can reach low altitudes, but also where their fluxes are most strongly influenced by atmospheric conditions.

Particle absorption is proportional to the atmospheric density. At altitudes below 1000 km the density of the neutral atmosphere can be well approximated by an exponential function with an altitude dependent scale height which at 400 km, the Mir altitude, is approximately 60 km (David, 1994). The altitude gradient is responsible for the anisotropy (pitch–angle distribution, east–west effect) of the proton fluxes in the SAA (Watts *et al.*, 1987). Density is also a function of solar flux, local time, and season. It is high at high solar activity, around local noon, and during local summer, and low at weak solar activity, local midnight, and local winter, respectively.

In this paper we present an analysis of aspects of the atmospheric influence on the trapped proton fluxes in the SAA using measurements made by the Radiation Environment Monitor (REM) aboard the Russian space station Mir around 1995.

INSTRUMENT AND OBSERVATIONS

The observations cover the time from November 1994 until February 1996. During this period REM was accumulating data for more than 50% of the available time. 1995 was a suitable year for the study of atmospheric influence on trapped particles as it was characterized by the absence of strong solar events (except one on 18 October) which could have caused major changes in the inner belt configuration.

The REM instrument is mounted on the outside of the Mir space station, fixed on railings encircling the

Mir core module. The detector aperture is directed perpendicular to the length axis of the station, towards space. REM consists of two shielded silicon detectors measuring energy loss (ΔE) spectra of charged particles (Bühler *et al.*, 1995). The ΔE spectra are accumulated for 32 seconds and binned into 16–channel histograms. Channel energies range from 10 keV (0.2 MeV cm^2/g, 0.1×minimum ionizing energy (MIP)) up to more than 100 MeV (2 GeV cm^2/g, 1000×MIP). The main aperture is defined by an aluminium cone with an opening angle of ±45°. The aperture of the detector we use in this analysis (the "p–detector") is covered with 3 mm aluminium and an additional inner layer of 0.75 mm tantalum. The dome thickness defines the lower cut–off energy, E_{th}, for particles able to penetrate into the detection volume. For electrons E_{th} is approximately 2.6 MeV and for the protons 34 MeV, respectively. As the energy spectrum of the electrons in the Mir environment is steeply decreasing with energy, an efficient suppression of electron detection in the p–detector is obtained.

TEMPORAL VARIATIONS OF THE SAA

In order to measure the temporal variations of the radiation environment in the SAA we calculate the energy deposit in the p–detector per day. In the following we define the SAA to be the rectangular region confined by the limits $-80° \leq$ longitude $\leq 40°$, latitude $\leq 0°$. We select periods of 24 h and calculate the average deposited dose in the SAA. Periods for which not at least 80% of the data are available are rejected. For the accepted periods the few missing points are interpolated.

The result is presented in Figure 1. Three month average daily doses accumulated in the SAA (bold line with dots) are plotted versus time. In the same figure we also show the three month average 10.7 cm radio solar flux ($F_{10.7\text{A}}$, dash–dotted line). In empirical atmospheric models the radio solar flux is used as a measure for the heating of the atmosphere by the sun and is one of the main parameters influencing the atmospheric density distribution.

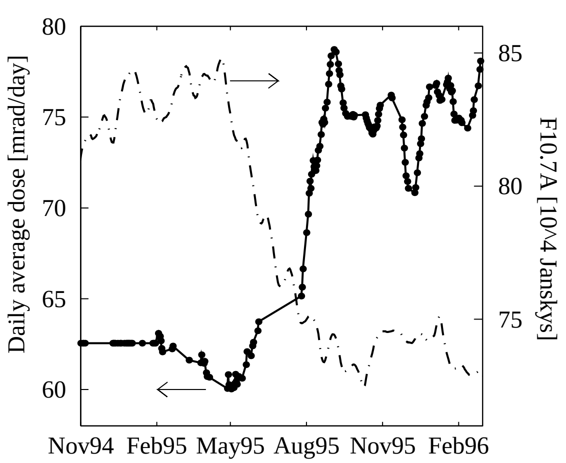

Fig. 1: Daily average SAA dose accumulated in the REM p–detector (dots) and three month average 10.7 cm solar flux (dash–dotted line). The decrease of the solar flux in the middle of 1995 is followed by a general increase of the trapped proton fluxes in the SAA. The short–time variations of the SAA dose are partly due to different coverage of the SAA by the daily measurements.

A general increase of the SAA daily doses of about 25% from November 1994 to February 1996 is observed. This increase nicely coincides with the lowering of the solar irradiance. Using the MSIS model (Hedin, 1991) to calculate the atmospheric density we find that the lowering of $F_{10.7\text{A}}$ by the observed amount causes a decrease of the atmospheric density in the SAA at altitudes between 100 and 400 km by typically 20%, which could explain the increase of the particle fluxes in the SAA.

The expected influence of local time and season on atmospheric density is of magnitude similar to the effects discussed before. The seasonal variation, due to the changing inclination of the earth's rotation axis with respect to the sun during the year, is swamped by the solar flux variation and can not be seen. We have also investigated the local time dependence but have not detected a systematic difference of the SAA radiation between noon and midnight. The loss processes are too inert to follow these short–term variations.

ANISOTROPY

Due to the altitude gradient of the atmospheric density the particle fluxes in the SAA are a function of altitude. For protons with energies around 100 MeV it has been shown that the altitude dependence of the fluxes at Mir altitude can be described by a power law

$$j(h) = j_0 h^n \qquad (1)$$

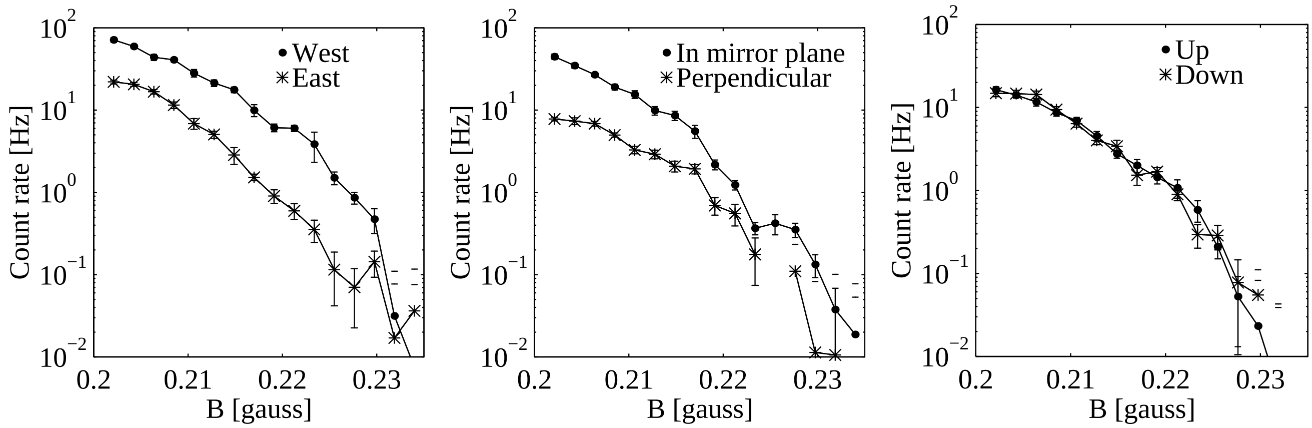

Fig. 2: Anisotropy of 200 MeV proton flux at 1.35< L <1.45. Measured fluxes in different directions are compared (l.t.r.): magnetic east and west, in mirror plane and perpendicular to mirror plane, along field line in positive and negative direction.

with a power index of approximately 4.9 (Heckman and Nakano, 1969). For a given L–shell value the altitude reached is a function of pitch angle. Particles with small pitch angles dip deeper into the atmosphere and are lost. This causes a depletion of the pitch angle distribution at small angles and a "pancake" distribution biased towards 90°.

There is a limiting pitch angle $\alpha_{\rm LC}$ below which stable trapping is made impossible by the atmospheric losses. The cone of pitch angles smaller than $\alpha_{\rm LC}$ is assumed to be empty and is called the loss cone. The altitude gradient is also responsible for the east–west effect. For protons the cyclotron motion is anti clock–wise with respect to the magnetic field vector. In the SAA at Mir altitude the magnetic field has a dip angle I of typically 50° and points toward north. Thus the guiding center of a particle arriving from the east at the detector (actually magnetic east, but differences are small, ≈7°) is located below the point of observation and for a particle arriving from west it is located above the point of observation. Particles coming from east will have experienced denser parts of the atmosphere than those from the west and will be more absorbed. The altitude difference Δh of the guiding centers and the detector is given by

$$\Delta h = r_{\rm c} \cos I \sin \phi \tag{2}$$

where r_c is the cyclotron radius and ϕ is the angle between magnetic east and the direction of observation measured in the mirror plane. Combining Eqs. (1) and (2) the ratio of the east $j_{\rm E}$ and west $j_{\rm W}$ fluxes can be calculated (Watts *et al.*, 1987)

$$\frac{j_{\rm W}}{j_{\rm E}} = \left(\frac{h_0 + \Delta h}{h_0 - \Delta h}\right)^n \tag{3}$$

In our analysis of the anisotropy we use the count rates of channels 4 and 5 of the p–detector. Channels 4 and 5 contain detections of protons with incident energies above 200 MeV. Although these high energy protons can also penetrate from out of the detector aperture, in that case they will lose energy in the surrounding material before they cross the sensitive part of the detector and will thus deposit more energy in the detector. Therefore the selected channels contain only particles coming through the aperture, which is necessary to measure directional fluxes. However, the opening angle is ±45°. Another advantage is that $j_{\rm W}/j_{\rm E}$ is an increasing function of the energy and will thus be best seen for these high energy particles. For a 200 MeV proton with pitch angle 90° the cyclotron radius is ≈100 km. Using I=50°, ϕ=0°, and $n = 4.6$, Eq. (3) yields $j_{\rm W}/j_{\rm E}$=4.9. Taking into account the finite opening angle of the REM detector we can expect to measure a somewhat lower value.

To see the difference of the fluxes in different directions the data has to be properly selected. We select only data for which the daily dose is between 60 and 80 mrad to separate anisotropy effects and temporal variations. The altitude of the Mir station has only varied by a few kilometers. However, we correct the data for the station altitude with reference to 400 km using Eq. (1). As the proton fluxes are also a function of B and L we have to bin the data into B–L bins and then deduce the anisotropy for each bin separately.

In Figure 2 the measured effect for three different pairs of directions is shown for L=1.4. The first panel shows the difference between the west and east fluxes. The average ratio $j_{\mathrm{W}}/j_{\mathrm{E}}$ is 4.3 which agrees well with the predicted value. In the next panel, measurements made with the detector axis in the mirror plane are compared with measurements made with the detector axis perpendicular to the mirror plane (in loss cone). The measurements made in the loss cone are not zero because of the large aperture of the detector. However there is a clear difference between the two directions. A more accurate determination of the loss cone is discussed below. The third panel (rightmost) shows data measured along the local field line, in positive and negative direction, respectively. From the anisotropy theory sketched above no difference is expected, as is confirmed by the observations.

Loss cone

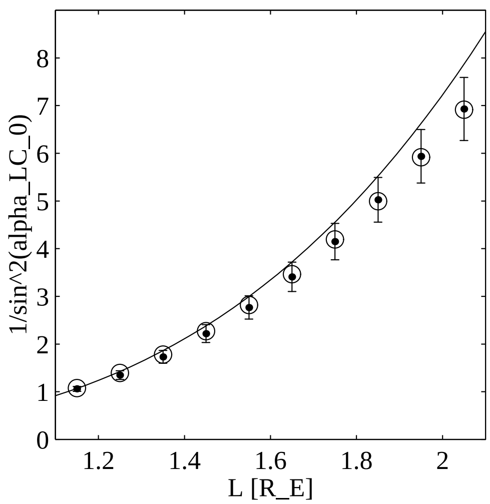

Fig. 3: Equatorial loss cone angle versus L–shell parameter. The points are the results of the REM measurements. Assuming 120 km to be the lowest possible altitude to be reached by trapped particles the loss cone can be calculated, which is represented by the circles. The solid line shows a result obtained with the AP–8 model data.

In order to determine the loss cone angle α_{LC} we utilize the fact that for a given L–shell, the omnidirectional fluxes measured over the whole range of magnetic field strength can be used to deduce the pitch angle distribution (PAD). REM neither measures strictly omnidirectional fluxes nor do the measurements cover the whole range of B–field values. However, by combining a large number of observations we obtain a good approximation of the omnidirectional flux and by using a model for the PAD with few free parameters, one of which is the loss–cone angle, α_{LC} can be determined. As a model for the PAD we use the one described by Badhwar and Konradi (1990). The result of this analysis is shown in Figure 3 where $\sin^{-2}\alpha_{\mathrm{LC}_0}$ is plotted versus L (dots with errorbars). The index 0 denotes equatorial values.

A simple approach is to assume that particles dipping below a certain altitude h_{lim} will be lost from stable trapping. To this limiting altitude corresponds a limiting pitch angle α_{lim}. The circles in Figure 3 represent this limiting pitch angle for h_{lim}= 120 km. A perfect agreement between this simple model and the measurements can be noted. The bold line in the same figure has been calculated with the equation $\sin^{-2}\alpha_{\mathrm{LC}} = 0.66L^{3.452}$ which has been used to describe the loss cone of the AP–8 data set (Daly and Evans, 1993). The deviation of this relation from the actual results is a manifestation of the changes of the magnetic field since 1965 when AP–8 was built.

SUMMARY

We have presented data measured aboard Mir with REM and have discussed aspects of the atmospheric influence on the trapped proton fluxes in the SAA. According to a decrease of the radio solar flux, the dose rates measured in the SAA have increased in 1995 by ≈25%. The anisotropy of the measured particle fluxes (east–west effect, loss cone) can be accounted for by basic models. In this study we did not consider energy dependencies. However, it is possible to deduce energy spectra from REM measurements, which will be included in further work.

ACKNOWLEDGMENTS

We thank M. Beliaev, N. Shvez, and L. Maslennikov for their assistance in preparing the data. This study was supported by ESA/ESTEC/WMA Technology Research Contract 11108/94/NL/JG(SC).

REFERENCES

Badhwar, G.D. and A. Konradi, Conversion of omnidirectional proton fluxes into a pitch angle distribution, *J. Spacecraft and Rockets*, **27**, 3, 350 (1990).

Bühler, P., S. Ljungfelt, A. Mchedlishvili, N. Schlumpf, A. Zehnder, L. Adams, E. Daly, and R. Nickson, *Instr. and Meth. in Phys. Res.* **A368**, 825 (1995).

Daly, E.J. and H.D.R. Evans, Problems in radiation environment models at low altitudes, *Memorandum ESA/ESTEC/WMA/93–067/ED* (1993).

David, R.L., *Handbook of Chemistry and Physics*, 74th edition, (1994).

Heckman, H.H. and G.H. Nakano, Low–altitude trapped protons during solar minimum, *J. Geophys. Res.*, **74**, 14, 3575 (1969).

Hedin, A.E., Extension of the MSIS Thermospheric Model into the Middle and Lower Atmosphere, *J. Geophys. Res*, **96**, 1159 (1991).

Watts, J.W., T.A. Parnell, and H.H. Heckman, Approximate angular distribution and spectra for geomagnetically trapped protons in low–earth orbit, *Conference proceedings on high–energy radiation in background space*, Sanibel Island, FL (1987).