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Correlation of Upper-Atmospheric ^{7}Be with Solar Energetic Particle Events

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Abstract. A surprisingly large concentration of radioactive ^{7}Be was observed in the upper atmosphere at altitudes above 320 km on the LDEF satellite that was recovered in January 1990. We report on follow-up experiments on Russian spacecraft at altitudes of 167 to 370 km during the period of 1996 to 1999, specifically designed to measure ^{7}Be concentrations in low earth orbit. Our data show a significant correlation between the ^{7}Be concentration and the solar energetic proton fluence at Earth, but not with the overall solar activity. During periods of low solar proton fluence, the concentration is correlated with the galactic cosmic ray fluence. This indicates that spallation of atmospheric N by both solar energetic particles and cosmic rays is the primary source of ^{7}Be in the ionosphere.

1. Introduction

An extraordinarily high concentration of radioactive ^{7}Be (53.3 d half life) at an altitude of 320 km or above has been inferred from measurements on samples of NASA's Long Duration Exposure Facility (LDEF) after its return to Earth in January 1990 [*Fishman et al.*, 1991; *Phillips et al.*, 1991]. The ^{7}Be was observed on the leading surfaces of LDEF and not on the trailing surfaces, suggesting that it was swept up from the residual atmosphere. The minimum concentration of ^{7}Be needed to explain the observed activity is ~10^{-7} atom cm^{-3} at or above 320 km. This is equivalent to a relative concentration of ~4×10^6 atom g^{-1} of air, which is ~2000 times higher than balloon measurements in the stratosphere where most of the ^{7}Be is believed to be produced by cosmic-ray spallation of nitrogen and oxygen [*Lal and Peters*, 1967]. This concentration is also three orders of magnitude greater than the calculated production in situ by cosmic ray interactions with the upper atmosphere at orbital altitudes [*Phillips et al.*, 1991]. Atmospheric diffusion calculations at solar maximum for atomic ^{7}Be produced by cosmic rays suggested that gravitational fractionation may explain up to 25% of the enrichment at LDEF altitudes [*Petty*, 1991]. However, it is likely that the ^{7}Be is ionized [*Gregory*, 1996] and it is unknown how this will affect the calculations.

It has also been suggested [*Gregory*, 1996; *Share and Murphy* 1997] that the large solar flares and extraordinarily intense SEP events at the Earth in the fall of 1989 contributed to the extraordinary concentration of ^{7}Be observed by LDEF. From the calculations of *Masarik and Reedy* [1995] we estimate that the ^{7}Be production rate by the SEP in October 1989 at latitudes >60° was 100 times the global GCR production rate. These intense SEP events may also have enhanced the upward transport of ^{7}Be due to the effects of heating and expansion of the upper atmosphere [*Phillips et al.*, 1991]. ^{7}Be is produced in solar flares when accelerated α-particles fuse with ^{4}He in the solar atmosphere [*Kozlovsky and Ramaty*, 1974; *Kuzhevskij and Lur'e*, 1997] and these may also have contributed under optimistic transport conditions [*Share and Murphy*, 1997].

2. Recent ^{7}Be Experiments

As a follow-up to the LDEF observations, stainless steel foils were flown on a series of Russian spacecraft beginning in March 1996 and continuing until December 1999. On the COSMOS spacecraft a 10x10 cm foil was fixed to a holder attached to the inside lens cover of the Earth-pointing camera such that it was exposed to the ram direction (direction of forward motion) when the cover was open and protected when the cover was closed during launch and reentry. On the RESURS F1 spacecraft a 20 cm diameter foil was mounted to a holder attached to a telescopic arm which extended 65 cm to expose the foil to the ram direction. The arm was contracted into a pill box for protection during reentry. On the latest flight, a foil was also attached to the back of the holder facing the anti-ram direction. Upon recovery, the foils were flown to the U.S. and the 478 keV gamma-ray from decay of ^{7}Be was counted with a 115% n-type germanium detector 180 m underground in the Lawrence Berkeley National Laboratory

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Table 1. Orbital Parameters and Collected ^{7}Be Activities

Spacecraft	Launch Date	Recovery Date	Days in Orbit	Be-7 Activity ± Std. Dev. (Bq/m^2)	Perigee (km)	Apogee (km)	Inclination (degrees)	Period (min)
1. LDEF launch	06-Apr-84				509	509	28.4	94.7
recovery		20-Jan-90	2115	770 ± 40	320	320	28.4	90.9
2. COSMOS 2331	14-Mar-96	11-Jun-96	89	3.0 ± 0.5	184	350	67.1	89.9
3. RESURS F-1M	18-Nov-97	13-Dec-97	25	4.5 ± 0.3	196	252	82.3	88.6
4. COSMOS 2348	15-Dec-97	14-Apr-98	120	5.2 ± 0.5	176	370	67.2	89.6
5. COSMOS 2358	24-Jun-98	22-Oct-98	120	22.2 ± 0.9	167	334	67.1	89.5
6. COSMOS 2365	18-Aug-99	15-Dec-99	119	5.5 ± 0.8	176	368	67.0	90.0
7. RESURS F-1M	28-Sep-99	22-Oct-99	24		174	219	82.3	88.6
ram facing				1.7 ± 0.4				
anti-ram facing				0.2 ± 0.2				

Low Background Facility at Oroville, CA [*McDonald et al.*, 1998]. Table 1 gives the flight parameters and the ^{7}Be activity corrected to date of recovery for the LDEF, COSMOS and RESURS F1 flights. The activity in the anti-ram facing direction was essentially zero confirming that the ^{7}Be atoms were deposited by impact with the upper atmosphere.

3. Correlation with Solar Particle Events

We have compared the ^{7}Be data to GOES satellite data in order to determine whether they were correlated with solar energetic protons (SEP), with galactic cosmic rays (GCR) or with the overall solar activity. We used the GOES daily average solar x-ray fluence as a measure of solar activity and the GOES >10 MeV daily proton fluence to monitor the SEP intensity (data from the NOAA National Geophysical Data Center [*NGDC*, 2000].) Since the baseline on the proton fluence data is arbitrary, we subtracted off a running average of the daily proton fluence during periods when no excess solar activity is evident. For the GCR we used the monthly averages of the daily cosmic-ray proton fluence >100 MeV measured by the Chicago instrument on the IMP-8 satellite [*Lopate*, 2000], excluding periods of excess solar activity.

The ^{7}Be activities observed on LDEF, COSMOS and RESURS F1 are shown in Figure 1 along with the daily solar proton fluence, the daily cosmic ray fluence and the average solar x-ray fluence over the time periods of 1989-1990 and 1995 to July 2000. The height of the bars shows the observed ^{7}Be activities and the width of the bars indicates the period the foils were in orbit. Evidence that the activity accumulates with time in orbit is shown by the relative heights of the two overlapping COSMOS and RESURS F1 flights in the fall of 1999 with durations of 119 and 24 days, respectively.

Figure 1 reveals a strong correlation between the ^{7}Be activity accumulated on the foils and the solar proton events. Two moderately intense events occurred in August-October

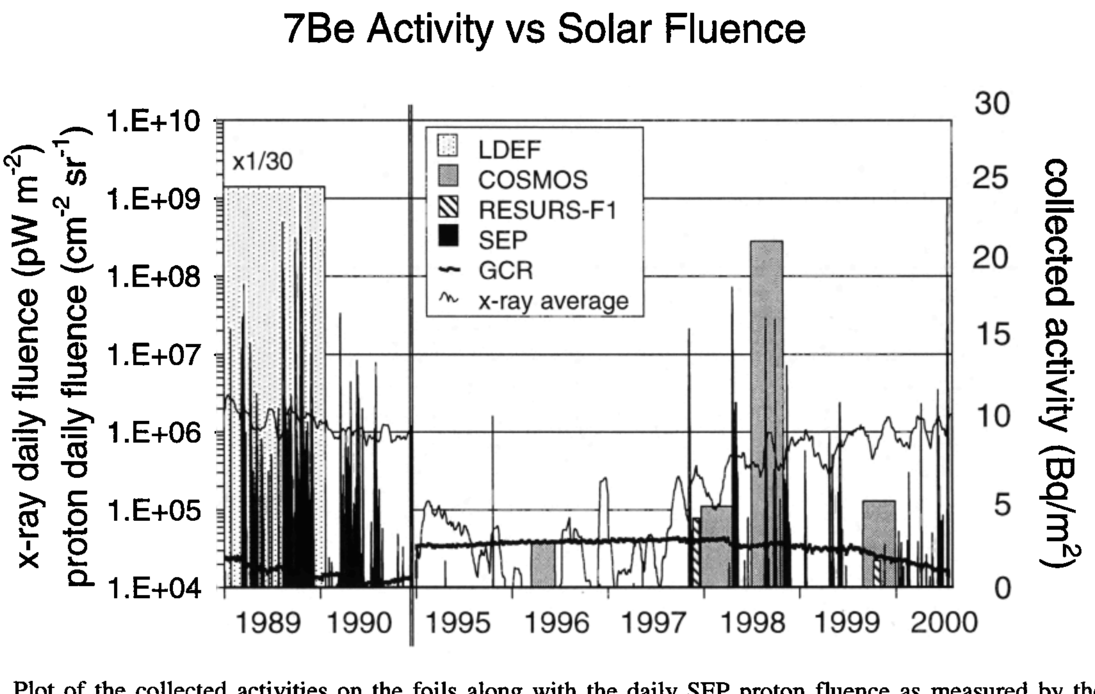

Figure 1. Plot of the collected activities on the foils along with the daily SEP proton fluence as measured by the GOES satellites, the daily GCR fluence from the IMP-8 satellite and the smoothed solar x-ray fluence (in units of pW m^{-2} chosen to fit on the same graph.) The width of the bars shows the time in orbit and the height gives the collected ^{7}Be activity (scale at right.) The observed activity is apparently correlated with the intensity of the solar proton fluence during or closely preceding the flight. No correlation is seen with the solar x-ray intensity.

1998 while a COSMOS flight was in orbit and this flight shows the highest accumulated activity. The lowest measured activity for a COSMOS flight was in the spring of 1996, recovered eight months after a small solar proton event in October 1995. However, the ^{7}Be activity is not correlated with the solar x-ray fluence, which has been gradually rising since solar minimum in May 1996. This is apparent from the low ^{7}Be activities observed for the two flights in the fall of 1999 during a period of relatively high solar x-ray fluence.

We have developed a model for estimating the ^{7}Be activity observed on the foils. Assume that a solar particle event introduces a pulse of ^{7}Be atoms into the upper atmosphere that is proportional to the >10 MeV SEP fluence P_S observed by the GOES satellite at a time t_0. The ^{7}Be density C in orbit at a time $t > t_0$ is given by

$$C\{t\} = D_S\, P_S\, e^{-\lambda(t-t_0)} \qquad (1)$$

where the time constant λ is the inverse ^{7}Be mean-life (76.9 days)$^{-1}$. The ^{7}Be production parameter D_S will depend on the mechanisms for production and transport of the ^{7}Be to orbital altitudes and on the energy spectrum of the solar protons. The ^{7}Be production cross-section for protons on nitrogen has a threshold at about 11 MeV, rises to a peak of about 45 mb near 20 MeV and then falls to a plateau of about 10 mb above 40 MeV [*Bodemann et al.*, 1993].

Assume that the foil is exposed to the ram direction between times t_1 and t_2 and sweeps up the ^{7}Be in orbit at a rate $R = F\,V$ where V is the satellite velocity and $F \le 1$ is a sticking factor for the atoms on the foil. Accumulation occurs from time $t' = \text{maximum}(t_0,t_1)$ until time t_2. The areal density $B\{t\}$ on the foil at a time $t \ge t_2$ is then

$$B\{t\} = F V D_S P_S\,[(t_2 - t')]e^{-\lambda(t-t_0)}\,. \qquad (2)$$

If instead of a single SEP pulse P_S there are several pulses P_{S_i} at times t_{0_i} then the contributions are additive.

There is also a slowly varying background due to the GCR with a daily fluence P_{Gi} and a ^{7}Be production parameter D_G. We fit the data for a linear relationship between the measured activity and the calculated activity given by $\lambda\, B\{t\}$ with

$$B\{t\} = a_S\, Q_S\{t\} + a_G\, Q_G\{t\}] \qquad (3)$$

$$Q_j\{t\} = \sum_i P_{ji}[\lambda(t_2 - t'_i)]e^{-\lambda(t-t_{0i})} \qquad (4)$$

where $j = S, G$ for the SEP and GCR terms, respectively, and the sum is over the daily fluences for a one-year period prior to recovery of the foil or about five ^{7}Be mean-lives, beyond which the contribution is negligible. For computational convenience we multiplied by λ inside the sum in equation (4) and therefore must divide by λ outside. Comparing equations 2-4, the fitting parameters $a_j = F D_j V / \lambda$.

The best fit to the data is shown in Figure 2. The insert shows the relative SEP and GCR contributions to the fit. The three data points on the left were collected during periods of low SEP activity and are dominated by the GCR term. The remaining points to the right show generally increasing SEP influence. The fit gives $a_S = 3.0 \pm 0.2$ and $a_G = 8.7 \pm 2.1$ (atom m^{-2})/(cm^{-2} sr^{-1}). These errors do not reflect uncertainties due to the differences in the SEP and GCR spectra, in orbital altitude and inclination and in the transport mechanisms. With this caveat, we can estimate the production parameters as follows: the sticking factor F is assumed constant ≈ 1.0, the average velocity over all the flights is nearly constant, $V = 7626 \pm 23$ m s^{-1} and $\lambda = 1.505 \times 10^{-7}$ s^{-1}. Then the production parameters $D_S = 5.9 \pm 0.4 \times 10^{-11}$ and $D_G = 1.7 \pm 0.4 \times 10^{-10}$ (atom m^{-3})/(cm^{-2} sr^{-1}).

4. Summary and Conclusions

Following the original observation on LDEF, we have made collections of ^{7}Be from 1996 to 1999 on stainless steel foils deployed in the ram direction on spacecraft in low Earth orbit in order to better understand this phenomenon. We find that high orbital ^{7}Be concentrations are strongly correlated with SEP fluence occurring during or within a few months prior to the exposures. During periods of low SEP fluence the concentrations appear to be correlated with the solar modulated GCR intensity. Ground level ^{7}Be activity shows a similar correlation with the GCR intensity but no apparent SEP influence [*Ioannidou and Papastefanou*, 1994]. This difference may be due to the different energy spectra and composition of the SEP and GCR. The SEP spectra are much softer and therefore tend to interact higher in the atmosphere.

We also find no correlation of ^{7}Be concentration with overall solar activity, as monitored by the solar x-ray fluence. This suggests that the primary source of ^{7}Be at satellite altitudes is spallation of atmospheric N by solar energetic particles and cosmic rays.

We can make an independent estimate of the production parameters D_S and D_G starting with the ^{7}Be production rates in the atmosphere given by *Masarik and Reedy* [1995]. Using reasonable values for the atmospheric densities, the depths over which ^{7}Be is produced and the ^{7}Be enrichment factors above 100 km [*Petty*, 1991], we obtain estimates for D_S and D_G which agree with our measured parameters within a factor of two or three, well within the uncertainties of the calculations.

The low inclination and higher average altitude of the LDEF orbit compared to our subsequent exposures implies efficient transport both vertically and latitudinally to explain the data. A full understanding of the origin of ^{7}Be at satellite altitudes requires measurements that can be made as a function of time and orbital location. This would require a more sophisticated system for accumulating the ^{7}Be in orbit

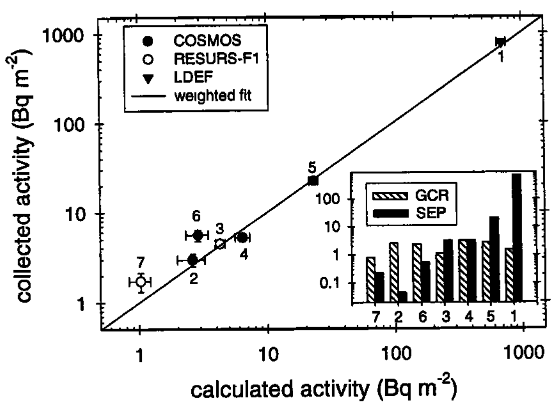

Figure 2. Plot of the collected activity on the foil vs. the calculated activity using equation 3. The vertical error bars represent uncertainties in the measurements and the horizontal error bars uncertainties in the fit. The numeric labels refer to the spacecraft in Table 1. The insert shows the relative SEP and GCR contributions to the fitted activities.

than has been possible to date. An alternative method for observing the production of ^{7}Be is through detection of the 429 keV gamma ray emitted when it is produced in its first excited state after spallation [*Ramaty et al.*, 1979]. We plan on searching for this line during SEP events using archival atmospheric gamma-ray data from *SMM* and new data from the upcoming High Energy Solar Spectroscopic Imager (HESSI) [*Lin*, 2000].

Some of the ^{7}Be observed in the upper atmosphere may come directly from the Sun after production by α-^{4}He fusion in flares [*Share and Murphy*, 1997] or directly from the solar atmosphere [*Kuzhevskij and Lur'e*, 1997]. It is possible that solar-produced ^{7}Be may be dispersed in interplanetary space and subsequently accelerated and transported to Earth by interplanetary shocks. A search for ^{7}Be in solar energetic particles using data measured outside the Earth's atmosphere is key to establishing any direct solar contribution. However, this may be a difficult measurement even for instruments on the Advanced Composition Explorer (ACE) [*Mason et al.*, 1998; *Stone et al.*, 1998].

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