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ABSTRACT

Using 4 years of data from an E.A.S. experiment on Musala Peak, we have performed a power-spectral analysis on the flux of $\sim 6\times10^{13}$ eV primary cosmic rays. Statistically-significant non-Poissonian fluctuations are found, with a power spectrum proportional to f^{-1} for frequencies 2×10^{-8} Hz $\leq f \leq 10^{-5}$ Hz. Possible sources of these fluctuations are discussed: instrumental drifts, data analysis techniques, meteorological effects, and scattering by interstellar electromagnetic field irregularities.

АННОТАЦИЯ

Определен спектр мощности потока первичных космических лучей с энергией $\sim 6\times10^{13}$эВ с помощью данных, полученных в течении 4-х лет в эксперименте по широким атмосферным ливням, проведенном на пике Мусала. Статистически достоверная флуктуация носит не пуассоновский характер, и уменьшается по закону f^{-1} в интервале частоты 2.10^{-8} Герц $\leq f \leq 10^{-5}$ Герц. Рассмотрены возможные причины полученной флуктуации: нестабильность аппаратуры; методы, использованные при обработке данных, метеорологические эффекты и рассеяние на электромагнитных неоднородностях в межпланетном пространстве.

KIVONAT

A Muszala csucson végzett kiterjedt légizápor kisérlet 4 év alatt kapott adatainak felhasználásával meghatároztuk a 6×10^{13} eV körüli energiáju primer kozmikus sugárzás fluxusának power-spektrumát. Statisztikailag szignifikáns nem Poisson jellegü ingadozást találtunk, amely a 2×10^{-8} Hz$\leq f \leq 10^{-5}$ Hz frekvenciatartományban f^{-1} szerint csökken. Megvizsgáljuk a kapott fluktuáció lehetséges okait: a berendezés instabilitását, az adatfeldolgozásnál alkalmazott módszereket, meteorológiai hatásokat valamint a csillagközi elektromágneses térben történő szóródást.

1. INTRODUCTION

The Extensive Air Shower experiment on Musala Peak has given evidence for a non-solar diurnal anisotropy /Gombosi, et al., 1975a/. The experiment has been run for several years with few major data gaps, and care has been taken in interpretation of the data to eliminate spurious temporal drifts. To verify the techniques used to eliminate spurious trends, we have performed a power spectral analysis of the flux observed at Musala. The statistically-significant fluctuations found and reported here are not due to long-term trends or detector drifts, to meteorological corrections, or to near-earth solar-system effects. They may originate in space far from earth. Several possible sources for the fluctuations are briefly discussed, although their large size /∿0.5%/ and their peculiar power spectral shape (f^{-1}) severely limit the possible production mechanisms.

2. THE OBSERVED POWER SPECTRUM

Four years of counting-rate data from the Musala experiment, composed of 3-hour average fluxes, were divided into 4 temporal periods. We calculated a power spectrum for each epoch, using the nested variance method /Owens, 1977a/. The four similar spectra were weighted by their 68 % ("1σ") confidence intervals and combined to give the "raw spectrum" in Figure 1. This is the spectrum of the relative flux,

$$n_r = \{J^* - \langle J \rangle\} / \langle J \rangle \equiv \Delta J^* / \langle J \rangle, \qquad /1/$$

where J^* is the observed flux and $\langle J \rangle$ is its long-term average, both corrected for meteorological effects /Gombosi, et al., 1975a/.

Random fluctuations due to counting statistics give a flat noise power spectrum of

$$P(f) = 2/\langle J\rangle \qquad /2/$$

/Owens and Jokipii, 1972/, where $\langle J\rangle = 2.5$/sec. As shown in Figure 1, this Poisson noise spectrum is important only for frequencies greater than $\sim 10^{-5}$ Hz.

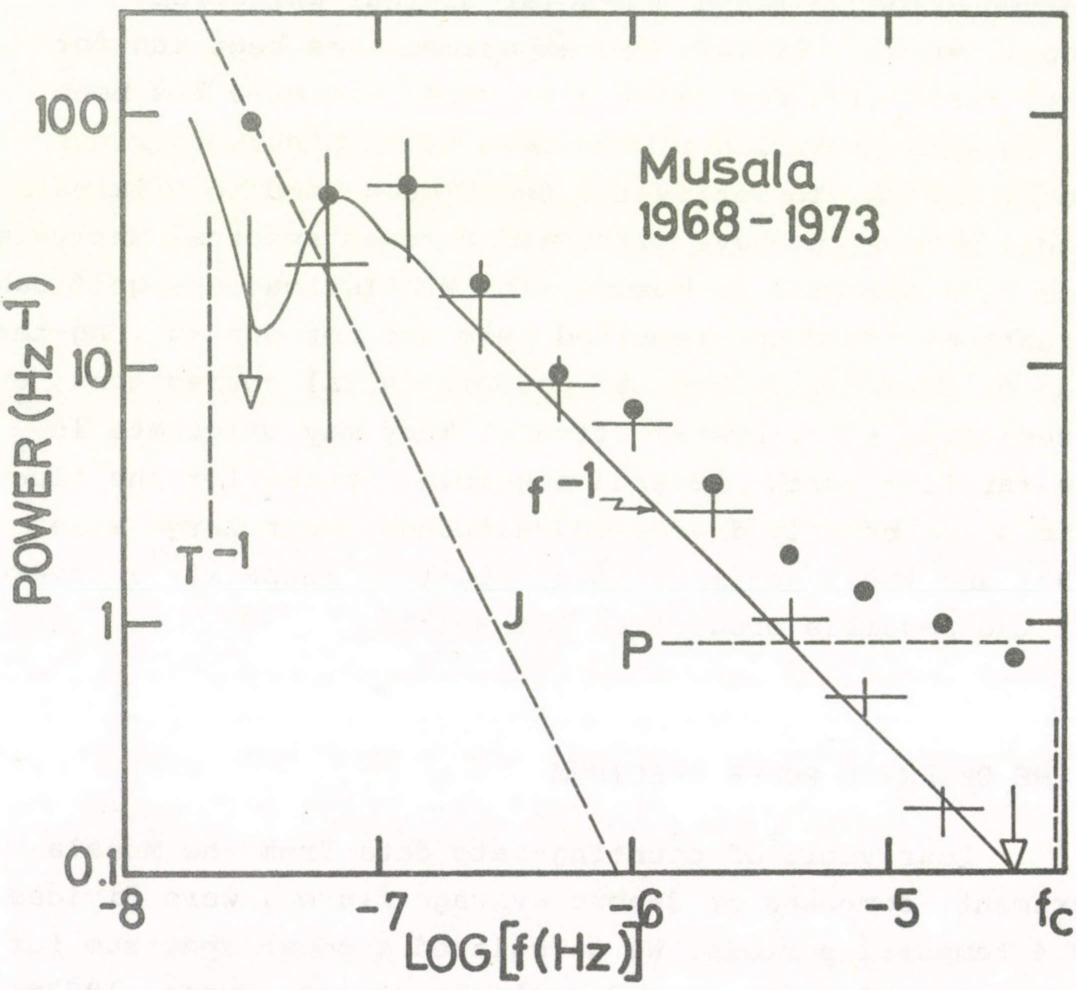

Fig. 1 Power spectra of the Musala fluctuations. Filled circles are the raw spectrum of n_r. Poisson noise level ("p") and contribution of counter-tube jumps ("j") are shown. Heavy bars give "observed spectrum" raw spectrum minus p and j spectra with 1σ confidence intervals. Solid curve is predicted result for a f^{-1} spectrum with linear trends subtracted, displaced vertically for clarity. Aliasing frequency is f_c.

The data used in these calculations had been corrected for drifting counter response by subtraction of a fitted line for each of the 5 counter-tube assemblies used. The counting-rate difference upon changing tubes was 2.5 %, and the de-trended data used here had residual "jumps" of ~0.6 % at the joints. Each of the 4 spectra had exactly one jump due to the residual tube-changing effect. For a single jump of size d = 0.6 %, the power spectrum is

$$P(f) = T\,d^2\,\{1-\cos(x)\}/x^2, \qquad /3/$$

where $x = \pi fT$ and $T \cong 4000\text{x}3\text{hr} \cong 4\text{x}10^7$ sec is the length of the data record. The spectrum of these jumps, averaged over the frequency intervals used in the power spectrum, is shown in Figure 1. It dominates the power only for very low frequencies. A similar conclusion is reached if one supposes that the temporal drift of the tubes has quadratic or higher-order trends.

The "observed spectrum" in Figure 1 is for the residual fluctuations with the contributions of Poisson counting statistics and tube-changing effects subtracted. Low-frequency components with $f \sim 1/T$ in this spectrum are reduced from the true level due to the linear trend subtraction employed in correcting for counter-tube replacement, as discussed by Owens /1977b/. Assuming that the true spectrum is a power law, $P(f) \alpha f^{-1}$, we show in Figure 1 /solid curve/ the power spectrum of the de-trended data. The curve fits the spectrum quite well.

We conclude that the true power spectrum of the Musala fluctuations - corrected for Poisson counting statistics, long-term counter drifts, and linear trend subtraction - is

$$P(f) = A/f \qquad /4/$$

with $A=4\text{x}10^{-6}\ \text{Hz}^{-1}$. This spectrum is observed over the entire frequency range analyzed, from $1/T$ to f_c, or for frequencies $2\text{x}10^{-8}\ \text{Hz} \lesssim f \lesssim 5\text{x}10^{-5}$ Hz. These fluctuations have an rms size ~0.5 %, similar to the Poisson noise /0.6 %/ in the original data. We note that the Musala fluctuations, with a 1/f spectrum, cannot be produced either by noise [which has a flat spectrum] or by long-term trends [which have spectra proportional to $1/f^2$].

3. METEOROLOGICAL AND SOLAR-SYSTEM EFFECTS

In the Musala experiment, the air-shower flux was assumed to be of the form

$$\Delta J/\langle J\rangle = B\Delta P + C\Delta T + \text{diurnal anisotropy terms} \qquad /5/$$

where the coefficients B and C giving the dependence of the flux on pressure /P/ and temperature /T/ were determined by least-squares regression /Gombosi, et al., 1975a, 1975b/. The data n_r used in the power-spectral analysis were pressure - and temperature-corrected,

$$n_r = \Delta J^{*}/\langle J\rangle = \Delta J/\langle J\rangle - B\Delta P - C\,\Delta T. \qquad /6/$$

We next show that fluctuations in n_r are not due to insufficiencies in the meteorological corrections.

The power spectra of observed pressure and temperature /at the P-120 mbar level/ for the Musala experiment are shown in Figure 2. Both spectra are fairly flat up to a characteristic frequency $f \cong 10^{-6}$ Hz [corresponding to variations with a period ~12 days] and have a shape of $P(f) \alpha f^{-2}$ for higher frequencies. These spectra are quite different from the observed Musala spectrum with a shape of 1/f.

We have performed a cross-spectral analysis on daily averages of Musala and the meteorological data, using the FFT method of Bendat and Piersol /1971/. For the cross power spectrum P_{xy} of x and y, the coherence γ is defined by the relation

$$\gamma^2 = |P_{xy}(f)|^2/\{P_{xx}(f)\; P_{yy}(f)\}. \qquad /7/$$

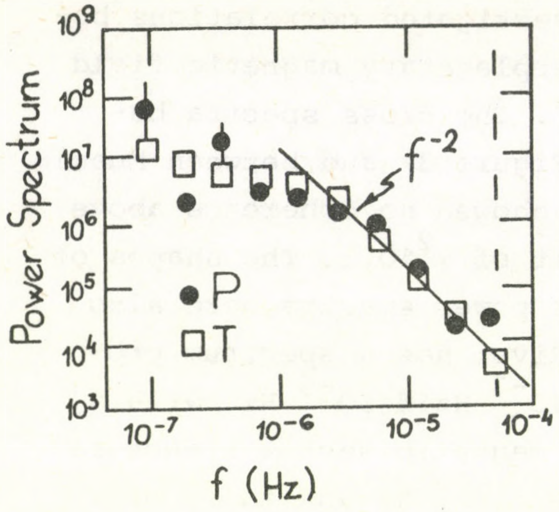

Figure 2 *Power spectra of meteorological data. Filled circles and squares give spectra of pressure (in mbar) and temperature (of the P-120 mbar level, in °K). Some 1σ confidence intervals are shown; they are smaller for higher frequencies.*

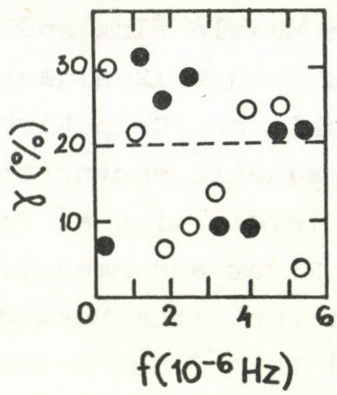

Figure 3 *Coherence between Musala and Pressure and Deep River. γ(f) is shown for cross--power spectra of Musala and pressure (solid circles) and Musala and Deep River Neutron Monitor (open circles), each with ν≈50 degrees of freedom. Dashed line at γ=0.2 gives bias level to be expected from uncorrelated data.*

For an estimate based on ν degrees of freedom, there is an inherent bias in the coherence estimates, so that two perfectly uncorrelated records have a coherence of

$$\gamma_{bias} = |2/\nu|^{0.5} \qquad /8/$$

Our analysis shows no significant coherence between Musala and P or T for any frequency range, above the bias level of $\gamma^2 \simeq 0.1$. This is illustrated for the cross-spectrum of Musala and P in Figure 3, where the average coherence is equal to the bias value. Thus the meteorological data "explain" less than 10 % of the variance in the observed fluctuations for Musala shown in Figure 1.

Next we considered solar effects and whether they could cause the observed Musala fluctuations. We used the flux of the Deep River Neutron Monitor /Steljes, 1971/ to investigate correlations between the solar-influenced lower-energy cosmic rays and Musala, and we investigated correlations between the Musala flux and the interplanetary magnetic field sector structure /Svalgaard, 1972/. The cross spectra between Musala and Deep River /see Figure 3/ and between Musala and the magnetic sector structure showed no coherence above the bias level, with an upper limit of $\gamma^2 \lesssim 0.1$. The shapes of the Deep River and magnetic sector power spectra were also very different from Musala. Deep River has a spectrum proportional to f^{-2} for frequencies 10^{-7} Hz$\lesssim f \lesssim 10^{-5}$ Hz, with a small shoulder at $\sim 5\times10^{-7}$ Hz. The magnetic sector structure has a spectrum with a maximum near 10^{-6} Hz and falls off for both higher and lower frequencies. Therefore, the primary energy of the Musala cosmic rays is sufficiently high that nearby solar-system effects contribute negligibly to the fluctuations.

4. DISCUSSION

We have shown that the 10^{14} eV cosmic-ray flux, as observed by the Musala experiment, has unexplained broad-band aperiodic fluctuations with an amplitude 0.5 %, a spectrum of 1/f, and time scales from days through a year. These fluctuations are not of meteorological origin and are not correlated with near-earth solar-system parameters. They are not due to long-term instrumental drifts or our data analysis techniques. Although extreme care has been taken to insure stable operation of the detector system, and linear trends have been taken into account, it is still possible that very small amplitude, long-term aperiodic variations in the sensitivity of the GM tubes are responsible for the observed variations. Similar analyses using data from other detectors could test this possibility. If the fluctuations are not instrumental, the remaining sources probably must be either interstellar or interplanetary cosmic-ray scintillations.

Interstellar scattering by random magnetic fields probably cannot account for the observed effect. From

Liouville's theorem /e.g. Owens and Jokipii, 1972/ one can derive

$$\Delta J^*/\langle J\rangle \approx (\Delta B/B)\,\delta\, F \qquad /9/$$

where $\Delta B/B$ is the relative field fluctuation, δ is the cosmic-ray anisotropy, and $F \lesssim 1$ is a frequency-dependent factor. For interstellar fluctuations whose wavelength (λ) is much smaller than the cyclotron radius (r_c) of the particles, as is the case here, $F \sim \lambda/r_c \ll 1$ since the particles effectively "average" the field fluctuations over a gyroperiod. For the observed anisotropy $\delta \sim 10^{-3}$ /Gombosi, et al., 1975a, 1975b/, even for $\Delta B/B \sim 1$ this process fails by several orders of magnitude to explain the Musala fluctuations.

A possible source is the "scintillations" of the high-energy cosmic rays in the electric fields that they see in the solar wind as they approach earth. The frozen-in magnetic field is convected outward by the solar wind with velocity V, giving rise to an electric field $\Delta E \sim \Delta B\, V/c$. For particles with charge $q=Ze$, the energy change $\Delta T \sim q\,\Delta E L$, where L is the size of the solar modulation region. Then we have

$$\Delta J^*/\langle J\rangle \approx \Gamma \Delta T/T \approx (\Gamma Z e V/cT)\,(\Delta B\ L), \qquad /10/$$

where $J(T) \sim T^{-\Gamma}$. Because of the magnetic sector structure, the fluctuations $\Delta B \sim \langle B\rangle$. Since the magnetic field changes throughout the solar system, the term (ΔB L) in equation /10/ should be interpreted as a path integral,

$$\int \langle B\rangle\, dx \qquad /11/$$

averaged over typical access paths in the solar system. The value $\Delta J^*/\langle J\rangle \sim 0.5$ % can be obtained if we take (ΔB L) $\cong 70$ /gammas/ /a.u./ and $Z \approx 25$. This model may be implausible because it requires ΔB L about a factor of 10 larger than estimated in equation /11/ and because it assumes that most of the $\sim 10^{14}$ eV primary cosmic rays are heavy nuclei. But it gives the magnitude and the approximate time scales of the observed fluctuations.

Clearly, the large amplitude of the Musala fluctuations poses a difficult problem in finding a plausible source, as does the unusual 1/f spectrum. Additional power-spectral analyses from E.A.S. and deep underground muon experiments would be very helpful in developing models for these fluctuations and in testing them.

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