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Cosmic Rays Underground and the Interplanetary Magnetic Field*

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Abstract. A multiple regression analysis is performed between the harmonic components of the underground cosmic-ray flux and the three components of the interplanetary magnetic field vector as measured by spacecraft. A significant linear regression is found between a cosmic-ray diurnal variation with a maximum at 6^h or at 18^h sidereal time, and the magnetic field component tangential to the earth's orbit.

Key words: Cosmic Ray Diurnal Variation – Interplanetary Magnetic Field.

The phase of the diurnal variation of the cosmic-ray flux, as observed at underground stations, shows changes depending on the direction of the interplanetary magnetic field (Regener and Swinson, 1969). This effect is illustrated on the harmonic dial of Fig. 1. The segments of the broken lines represent, by their length and direction, the amplitude and the phase of the diurnal variation for each day. Positive and negative signs signify, respectively, magnetic fields away from the sun and toward the sun according to the spacecraft measurements reported by Wilcox and Colburn (1970). The cosmic-ray data are from the Embudo, N. M. underground station at a depth of 40 m.w.e.

In the present paper we demonstrate a quantitative relationship between the diurnal variation of the underground cosmic-ray flux and the interplanetary magnetic field. Our method is a multiple linear regression analysis of cosmic-ray data observed underground at Embudo Cave, New Mexico and at Mount Chacaltaya, Bolivia, in relation to data on the interplanetary magnetic field as recorded by the spacecrafts Explorer 28 and 33. For each day, the measured diurnal variation of the cosmic-ray flux is treated as a vector in the plane of the harmonic dial, with two orthogonal harmonic

* To Prof. G. Pfotzer in honor of his 65th birthday.

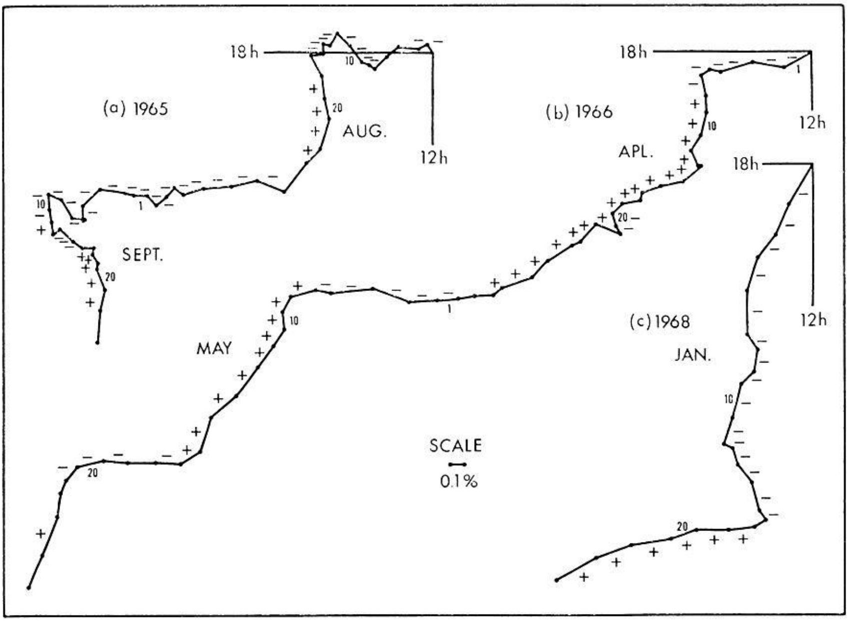

Fig. 1. Summation dial in solar time for the diurnal variation of the cosmic-ray flux at the Embudo underground station. Positive and negative signs indicate the direction of the interplanetary magnetic field

components U (positive toward 6^h) and V (positive toward 0^h). We correlate these with the mean for each day of the measured components X, Y and Z of the interplanetary magnetic field vector, where component X is directed from the earth toward the sun, Y is tangent to the earth's orbit and positive in the direction opposite to that of the earth's velocity around the sun, and Z is directed toward the ecliptic north pole. Days on which the spacecraft was within the magnetosphere are omitted, and on other days we have no cosmic-ray data; we include only those days on which both the cosmic-ray data and the spacecraft data are complete. Using cosmic-ray data from the Embudo Station, we have 500 suitable days covering the period from June 6, 1965 to September 29, 1968; from the Chacaltaya station, we have only 174 good days between January 25, 1967 and May 20, 1968.

In our multiple regression analysis, we treat U and V (the harmonic components of the cosmic-ray diurnal variation) as dependent variables and X, Y, and Z (the mean daily components of the interplanetary magnetic field vector) as independent variables. We are aware that this treatment is formal, since we are assuming no physical mechanism for the interaction between the interplanetary magnetic field and the cosmic-ray flux. In addition, X, Y, and Z are components of a single vector and thus not unrelated to each other. Finally, the physical relationship between the dependent and independent variables is not expected to be a linear one. Nevertheless, the outcome of this study might be useful in the discussion of models for the modulation of the cosmic-ray flux by the interplanetary magnetic field.

Tables 1 and 2 show for the Embudo and Chacaltaya data, respectively, the multiple regression coefficients[1] obtained for U and V on the harmonic dial with respect to the magnetic field components X, Y and Z, using several different methods of treating the data. The columns labeled X, Y, Z and k display, for each line labeled U and V, the respective multiple regression coefficients a, b, c, d, e, and f and their standard errors, together with the constant terms k_U and k_V, corresponding to the best linear fit in the regression equations

$$U = aX + bY + cZ + k_U$$
$$V = dX + eY + fZ + k_V,$$

where X, Y and Z are the three components of the magnetic field in units of 10^{-5} gauss. The two harmonic components U and V of the cosmic-ray diurnal variation are given in units of a fractional amplitude of 10^{-3}, or one tenth of one percent of the average counting rate.[2] In the column labeled *Mean* appear the means of the two cosmic-ray diurnal amplitudes. The first column shows in what way the cosmic-ray data were treated before submission to the multiple regression program. The first two lines, labeled *Solar*, show the multiple regression coefficients obtained using the original harmonic components of the solar cosmic-ray diurnal variation.

In the cases marked *Sid.* the cosmic-ray harmonic components for each day are rotated, prior to the regression analysis, by an amount appropriate to a harmonic dial referred to sidereal time. The same rotation is performed in the cases marked *Antisid.*, but in the opposite sense, to ascertain the result of a manipulation that could not have a physical justification.

The cases marked *m.s.* represent attempts to reduce the possible effect of the large afternoon maximum of the solar cosmic-ray diurnal variation upon the sidereal multiple regression coefficients. The mean of the cosmic-ray amplitudes, as given under *Solar*, is subtracted from each of the daily values before rotation into sidereal coordinates; under *Mean* appears the mean of the values thus altered.

When dividing each year into 13 bins of 28 days (one bin is given an extra day to make 365 days), some bins of the Embudo data contain up

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1 We are indebted to Robert Zamora who did the computer work with the aid of the Statistical Package for the Social Sciences (Nie *et al.*, 1970).

2 Barometer-corrected cosmic-ray data are used. No account is taken of the deflection of the cosmic-ray primaries in the earth's magnetic field.

Table 1. Multiple regression coefficients, Embudo data, 500 days. (The units and the abbreviations are explained in the text; the values in parentheses are magnetic field means)

Treatment		*Mean*	*X* (.390)	*Y* (—.697)	*Z* (.035)	*k*
Solar	*U*	—.686	.002 ± .018	—.002 ± .017	—.030 ± .024	—.687
	V	—.761	.026 ± .017	—.017 ± .016	—.064 ± .023	—.781
Solar, wtd.	*U*	—.757	.006 ± .017	.009 ± .017	—.006 ± .023	—.753
	V	—.770	.032 ± .016	—.037 ± .016	—.055 ± .021	—.807
Sid.	*U*	—.111	—.014 ± .020	**.091 ± .019**	—.048 ± .026	—.040
	V	.108	—.039 ± .022	.058 ± .021	—.013 ± .029	.165
Sid., m.s.	*U*	.044	—.008 ± .016	**.078 ± .016**	—.059 ± .022	.104
	V	—.004	—.010 ± .018	.047 ± .018	—.005 ± .024	.033
Sid., wtd.	*U*	.052	—.016 ± .019	**.092 ± .019**	—.045 ± .026	.123
	V	.030	—.045 ± .021	.054 ± .020	.002 ± .027	.087
Sid., wtd.,	*U*	.058	—.014 ± .015	**.077 ± .015**	—.052 ± .021	.119
m.s.	*V*	—.004	—.017 ± .017	.042 ± .017	.007 ± .023	.031
Antisid.	*U*	.118	—.017 ± .022	.016 ± .021	—.035 ± .029	.137
	V	.044	—.046 ± .020	.017 ± .020	—.057 ± .027	.076
Antisid.,	*U*	—.008	.012 ± .018	.006 ± .017	—.026 ± .024	—.008
m.s.	*V*	.187	—.038 ± .017	.004 ± .017	—.067 ± .023	.207
Antisid.,	*U*	.035	—.018 ± .020	.003 ± .020	—.029 ± .027	.047
wtd.	*V*	.229	—.036 ± .020	.022 ± .020	—.059 ± .027	.263
Antisid.,	*U*	.001	.010 ± .017	—.008 ± .017	—.024 ± .022	—.008
wtd., m.s.	*V*	.233	—.032 ± .016	.006 ± .016	—.066 ± .022	.256

Table 2. Multiple regression coefficients, Chacaltaya data, 174 days. (The units and the abbreviations are explained in the text; the values in parentheses are magnetic field means)

Treatment		*Mean*	*X* (.230)	*Y* (—.780)	*Z* (—.066)	*k*
Solar	*U*	—1.362	.097 ± .067	—.013 ± .059	.128 ± .110	—1.386
	V	— .739	.140 ± .046	.086 ± .040	—.131 ± .074	— .713
Sid.	*U*	.584	—.073 ± .066	.165 ± .058	—.111 ± .108	.722
	V	.648	—.101 ± .062	—.053 ± .055	—.013 ± .101	.629
Sid., m.s.	*U*	.175	.015 ± .059	**.182 ± .052**	—.124 ± .096	.305
	V	.050	—.067 ± .054	—.067 ± .048	0	.013
Antisid.	*U*	.997	—.096 ± .065	.016 ± .058	.053 ± .106	1.035
	V	.088	—.005 ± .064	.061 ± .057	.159 ± .104	.148
Antisid.,	*U*	.273	—.020 ± .060	.014 ± .053	.061 ± .098	.293
m.s.	*V*	.069	.050 ± .055	.084 ± .049	.137 ± .091	.132

to three times as many usable days as other bins. Upon weighting all the data in each bin by an integer factor between two and six, depending upon the number of good days in each bin, we achieve a more uniform distribution in which the number of good days in the bins differ, at the most, by thirty percent. This procedure is used to further reduce the possible influence of the solar diurnal variation on the calculated coefficients in sidereal time. The results of the multiple regression analysis of the weighted data are displayed in the lines marked *wtd.* In the case marked *Sidereal, weighted, mean subtracted*, for example, the mean of the weighted data as shown under *Solar, weighted*, is subtracted from the cosmic-ray harmonic components U and V for each day. The sidereal rotation is applied, and this material is finally submitted to the multiple regression analysis. It is not appropriate to apply the weighting procedure to the Bolivia data of Table 2, since large portions of the year do not have usable data.

In both tables, the regression coefficients that are larger than three standard errors are shown in bold face. All of these relate the sidereal U (the 6^h component of the diurnal variation in sidereal time) to the Y component of the interplanetary magnetic field (directed opposite to the direction of the earth's velocity around the sun). The regression is positive: the coefficient at Embudo is near 0.08 ± 0.02, indicating that a Y-component of 10^{-5} gauss leads to a sidereal component of the underground diurnal variation of the cosmic-ray flux with a maximum at 6^h sidereal time and with an amplitude of 0.008 percent. Returning to the solar harmonic dial of Fig. 1, it is seen that the direction of the phase change in the solar diurnal variation corresponding to a reversal of the magnetic field depends on the time of the year. The sense of these phase changes is, essentially, that adduced by our regression equation.

Coefficients of lesser statistical significance are seen for V with Y at Embudo in sidereal time, also with a positive sign. The correlation with Y disappears consistently for the antisidereal cases. In solar time there is a positive correlation of V with X both at Embudo and in Bolivia. Scattered negative correlations of U and V with Z appear throughout Table 1. The regression coefficients do not depend strongly on the various treatments of the data, except for the separation into the solar, sidereal, and antisidereal time frames.

The present result for the correlation of U with Y is consistent with Swinson's (1969) proposal to account for the sidereal component in the underground diurnal variation of the cosmic-ray flux in terms of a local magnetic field effect in conjunction with a radial gradient (away from the sun) of the interplanetary cosmic-ray density.

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