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CORRELATIVE ANALYSES FOR GEOMAGNETIC INDICES, COSMIC-RAY INTENSITIES AND SUNSPOT NUMBERS RECORDED SINCE 1937

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A statistical study between the cosmic-ray intensities, the ΣKp-geomagnetic indices and the sunspot numbers, from 1937 to 1986 on monthly basis is presented. Our results suggest that the latitudinal dependence for the charged-particle propagation in the interplanetary space, forecast by the drift theory during a Hale cycle, is badly checked by correlative analyses inside solar-cycles phases. The strong correlation between cosmic-ray intensities and the ΣKp values obtained between the 19th solar-cycle maximum and the 20th one and the poor correlation between the 20th solar-cycle maximum and the 21st one may be explained taking into account that polar coronal holes have covered negligible areas towards the helioequator during the descending phase of the 19th cycle and vast areas during the 20th one.

ANÁLISE DE CORRELAÇÃO ENTRE ÍNDICES GEOMAGNÉTICOS, INTENSIDADE DE RAIOS CÓSMICOS E NÚMERO DE MANCHAS SOLARES DESDE 1937 – No presente trabalho é apresentado um estudo de correlação estatística entre a intensidade de raios cósmicos, o índice geomagnético ΣKp e o número de manchas solares, de 1937 a 1986, usando médias mensais dos dados coletados. A "drift theory" prevê uma dependência com a latitude na propagação das partículas eletricamente carregadas no espaço interplanetário, durante um ciclo de Hale. Os resultados obtidos e aqui apresentados contrariam essa previsão. O coeficiente de correlação entre a intensidade de raios cósmicos e os valores de ΣKp obtido no período compreendido entre o máximo do ciclo solar nº 19 e o máximo do nº 20 é elevado. Já o valor do mesmo coeficiente obtido no período compreendido entre os máximos dos ciclos nº 20 e nº 21 é baixo. Esses resultados podem ser explicados levando-se em consideração que os buracos coronais em direção ao equador solar recobriram áreas negligenciáveis durante a fase descendente do ciclo nº 19 enquanto que durante o ciclo nº 20 as áreas recobertas eram vastas.

1. INTRODUCTION

The study of solar-terrestrial relationships is an invaluable tool to understand temporal variations in the space environment. The STEP (Solar-Terrestrial Energy Program, 1990-1995) is, for instance, a good opportunity to improve our knowledge of the physical processes involved in the chain: Sun - Interplanetary medium - Earth. For this purpose, the study of cosmic-ray (CR) modulation, induced by solar activity via interplanetary processes, is particularly appropriate.

A four-station network of Compton-Bennet ionization chambers (Cheltenham / Fredericksburg, Christchurch, Godhavn and Huancayo) was established in the 1936-37 years (e.g. Lange & Forbus, 1948) and was followed in the fifties by a world-wide network of neutron monitors, which is still operational with the so-called IGY and NM-64 detectors (see Shea et al., 1984, for the status of this network and others related to the solar-terrestrial physics).

A statistical study between CR intensities, geomagnetic indices and sunspot numbers from 1937 to 1986, on a monthly and yearly basis, is in progress. In this paper we report the preliminary results obtained by means of correlative analyses for successive solar-activity cycles.

2. DATA USED AND METHOD OF ANALYSIS

A network of magnetic observatories monitors continuously the geomagnetic field and several geomagnetic indices are derived for statistical studies (e.g., Mayaud, 1980). The one used more frequently for solar-terrestrial physics has been the Kp-planetary

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index together with its daily sum (ΣKp) till the introduction of the aa index (Mayaud, 1972). In this research we will restrict the analysis to the ΣKp indices.

The oldest solar parameter available is the daily sunspot number (Wolf or Zurich number Rz; McKinnon, 1987). For many decades the scientific community defined the solar-activity cycle in terms of the time interval between successive minima in sunspots (about 11 years: Schwabe cycle; the solar-activity cycles have been numbered from 1755). Nevertheless, it was showed that the Sun's magnetic cycle lasts about 22 years (Hale, 1913; Hale & Nicholson, 1938). In each solar-activity cycle the sense of the heliopolar magnetic field is reversed around the sunspot maximum (Babcock, 1961). Hence, consecutive Hale semicycles are characterized by an opposite sign of the heliomagnetic-dipole moment. Charged particles in the heliospace may be influenced by the above conditions, due to the presence of gradients and curvature of the three-dimensional interplanetary magnetic field (charged-particle drift). An evaluation of the drift contribution to the CR transport is in progress since 1977 (Jokipii, 1986 and references therein); a parameter A is usually introduced in drift calculations (e.g. eq. (5) of Jokipii et al., 1977), being the heliomagnetic field status outward (inward) in the northern hemisphere when $A > 0$ ($A < 0$). For consecutive Hale semicycles the drift theory forecasts a different three-dimensional dependence for the charged-particle propagation in the heliospace (see Sect. 4).

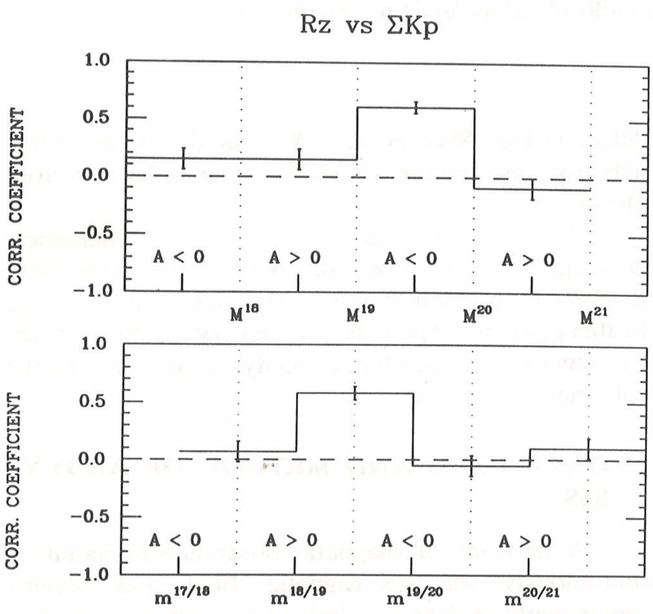

Figure 1. Correlation coefficients between the monthly Zurich sunspot number Rz and the geomagnetic index ΣKp for successive solar-cycle maxima (M^i, i = 17-21, upper panel) and successive solar-cycle minima ($m^{i/i+1}$, i = 17-21, lower panel). The parameter A indicates the heliomagnetic field status (see the text).

Correlative studies between geomagnetic, solar and CR parameters would show peculiar features related to the Schwabe and the Hale cycles.

To cover the time interval from 1937 (17th solar-cycle maximum) to 1986 (21st solar-cycle end), monthly averages of Rz and ΣKp indices are considered together with the CR monthly intensities registered by Cheltenham/Fredericksburg ionization chamber (1937-1969) and Deep River neutron monitor (1965-1986).

By using the method of least squares, the correlation coefficients of Rz vs. ΣKp and CRs vs. ΣKp have been evaluated for the following time intervals:

i) successive solar-cycle maxima M^i, i = 17-21 (i.e., from M^{17} to M^{18}: 1937-47; from M^{18} to M^{19}: 1947-57; M^{19} to M^{20}: 1957-68; from M^{20} to M^{21}: 1969-80);
ii) successive solar-cycle minima $m^{i/i+1}$, i = 17-21 (i.e., from $m^{17/18}$ to $m^{18/19}$: 1944-54; from $m^{18/19}$ to $m^{19/20}$: 1954-64; from $m^{19/20}$ to $m^{20/21}$: 1964-76; from $m^{20/21}$ to $m^{21/22}$: 1976-86).

3. RELATIONSHIP BETWEEN THE GEOMAGNETIC LEVEL AND THE SOLAR-ACTIVITY CYCLE

The upper panel of Fig. 1 shows the correlation coefficients obtained for Rz vs. ΣKp from one solar-cycle maximum to the next; the lower panel refers to solar-cycle minima. From this figure it appears that, except for the $m^{18/19}$ to M^{20} interval, a negligible correlation exists between Rz and ΣKp. Moreover, the temporal trend is practically the same in both panels (within the error bars) if a shift of one solar-activity semicycle is taken into account.

It is well known that temporal variations in the interplanetary plasma features at the Earth's location exert a strong influence on the terrestrial magnetosphere and, therefore, on the general geomagnetic activity level (the ΣKp-index may be viewed as a quantitative parameter of this level). Measurements *in situ* have shown that solar-wind parameters change considerably over different time scales and well-defined interplanetary plasma macrostructures have been identified (e.g., Hundhausen, 1972a, b; Burlaga, 1975; Neugebauer, 1983). The number, type and strength of these travelling interplanetary disturbances change according to the long-term solar-feature evolution. Several related parameters indicate the flare activity as the origin of transient solar-wind streams (Hundhausen, 1972b; Dryer, 1974; Iucci et al., 1979a, 1984; among others); this activity is described by the 11-year cycle. Instead, corotating solar-wind streams are interplanetary structures related to the plasma emitted from coronal holes (Krieger et al., 1973; Neupert & Pizzo, 1974; Nolte et al., 1976). These

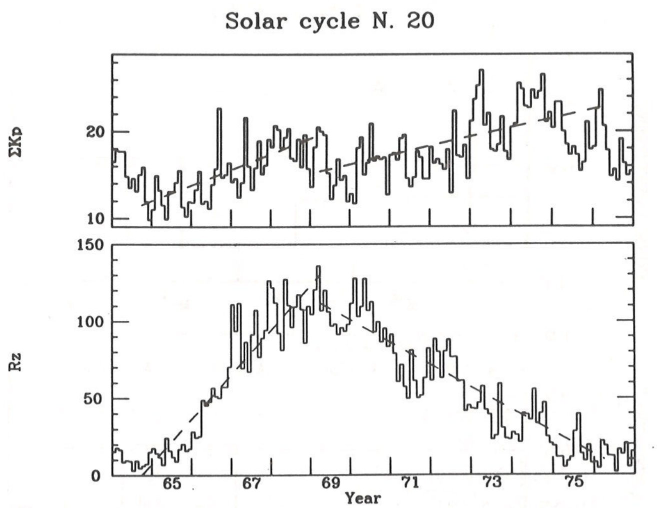

Figure 2. Temporal behaviours of the monthly averages of geomagnetic index ΣKp and sunspot number Rz for solar-cycle N. 20. Dotted lines indicate the linear trends during the ascending and descending phase of the cycle.

holes have a temporal evolution better related to the Hale cycle, due to the unipolar magnetic fields emerging from those regions. Other solar sources have been proposed for the weaker solar-wind disturbances but a general consensus has not yet been reached (see, for instance, Marsden, 1986).

Our knowledge of the long-term coronal-hole evolution has grown in the last 15 years (e.g., Zirker, 1977; Harvey & Sheeley, 1979; Hundhausen, 1981; Webb et al., 1984; Withbroe, 1986). Briefly, we distinguish between heliopolar holes and non-polar coronal holes. Large areas of the corona are covered by the heliopolar holes during sunspot minima; they decrease in the ascending phase and tend to disappear around maxima, at the same time of the weakening of the polar magnetic fields (e.g., Fig. 1 of DeVore & Sheeley, 1987). After the heliopolar-magnetic field inversion, the hole size grows and may cover a vast coronal area towards the helioequator during the descending phase of the solar-activity cycle, allowing broad and long-living recurrent high-speed solar-wind streams to overtake the Earth. Their geoeffectiveness should emerge during this phase and the minima. Non-polar corona holes occurred in solar regions where sufficiently extended unipolar-magnetic areas are found, and their life-time is shortened by the presence of active regions nearby. For this reason, even if non-polar coronal holes were observed in each phase of the solar-activity cycle, their geoeffectiveness via corotating high-speed streams during the ascending phase would be less evident than that of transient high-speed streams. While, during the descending phase their contribution must be added to that from polar coronal holes.

From the above summary we conclude that a very poor correlation between Rz and ΣKp can be expected, since the Rz-index is related to a fraction only of the travelling interplanetary disturbances (the transient ones). More precisely, we expect that during the ascending phase and the maxima the interplanetary medium conditions are dominated (but not completely described) by the transient stream series and the descending one by the corotating streams series. This, in turn, implies a positive (but not a strong) correlation between Rz and ΣKp for the first period and no correlation at all or a negative correlation for the second one. Figure 2 shows this effect for solar cycle N. 20. Figure 3 gives, instead, the correlation coefficients obtained for each solar-activity phase: during the ascending (As) phases the obtained coefficients are always positive and tend to have the same value. During the descending (D) phases they generally vanish or are negative, except for solar cycle N. 19 (D^{19}-phase). A possible explanation for this anomaly is the great flare activity observed in D^{19} which does not allow polar coronal holes to reach low latitudes. Incidentally, we note that the highest Rz values belong to the solar-cycle N. 19.

4. RELATIONSHIP BETWEEN THE GEOMAGNETIC LEVEL AND THE COSMIC-RAY INTENSITY

A three-dimensional dependence for the charged-particle propagation can be accounted for in a natural way in terms of CR drift (see Sect. 2). During a Hale cycle drift forecasts an easier access for CRs via: i) the heliomagnetic polar lines for $qA > 0$ (being q the charge of the particles considered); ii) the heliomagnetic current sheet for $qA < 0$. It implies for a positive (negative) heliomagnetic north (south) pole (i.e., $A > 0$) that positive CR particles drift equatorialwards to the current sheet, and then drift rapidly outwards along the current sheet itself. Negative particles, instead, drift inwards along the sheet, and then drift polewards. These particle motions are reversed for $A < 0$. There are several arguments both for and against the drift relevance (see, for instance, Tab. 1 in McKibben, 1988; Storini, 1990). In this context the correlative study by Shea & Smart (1981, 1985) is of particular interest. Their basic idea was to compare the solar-wind turbulence in the ecliptic plane (measured by a geomagnetic index) with the one encountered by the galactic CRs in their 3-dimensional propagation to the Earth. If CR drift works effectively, these interplanetary turbulences would be similar in the $A < 0$ periods and different in those with $A > 0$. They found that the correlation between the CR intensity (registered by the Mt. Washington neutron monitor) and the geomagnetic aa-index is good for $A < 0$ and poor for $A > 0$, in the

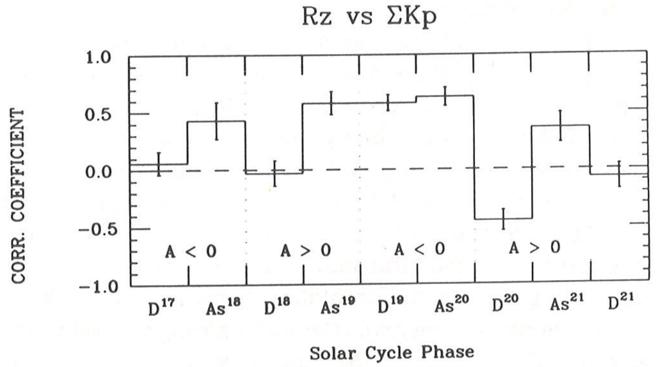

Figure 3. Correlation coefficients between Rz and ΣKp for each solar-activity phase. D^i and As^i indicate the descending and ascending phases of the cycle i (i = 17-21) respectively.

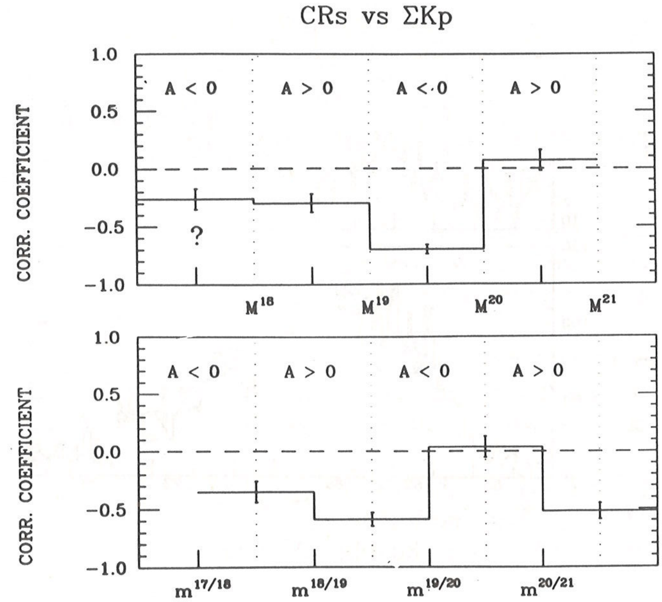

Figure 4. Correlation coefficients between the monthly CR intensity and the geomagnetic index ΣKp for the time periods as in Fig. 1. The CR intensities as measured by Cheltenham / Fredericksburg ionization chambers from 1937 to 1969 and by Deep River neutron monitor from 1965 to 1986 are used. The question mark indicates that in the time period M^{17} to M^{18} several data gaps in the ionization chambers prevent a reliable evaluation of the correlation coefficient.

time intervals included between the 19th and the 21st solar-cycle maxima. Filisetti et al. (1983) supported their results by using the Kp-index.

The correlation coefficients obtained in this paper between the monthly CR intensities and the ΣKp are reported in Fig. 4 (upper panel refer to solar-cycle maxima; the lower one refer to solar-cycle minima). The Shea and Smart idea holds from M^{18} to M^{21} while it drops from M^{17} to M^{18}. Again, shifting of one solar-activity semicycle the temporal behaviour of the correlation coefficients between successive minima, that for maxima is roughly obtained. Several data gaps found in the ionization chamber records during the first period (from M^{17} to M^{18}) prevent a reliable evaluation of the correlation coefficient. Moreover, no attempts has been made at this stage to check the long-term instrumental stability for the ionization chamber. It will be done in a subsequent paper by using data from the other three stations as reported by the Carnegie Institution. However, looking at the correlation coefficients obtained separately for each solar-activity phase (As and D phases), interesting features emerge (see Fig. 5):

i) the coefficients associated with the As-phases show always a more or less negative correlation between CRs and ΣKp;
ii) the coefficients related to the D-phases are variables, and always smaller than 0.5, except for D^{19}.

From CR-drift theory it could be inferred that: i) the coefficients for As-phases of the even cycles should be higher than those for the odd ones; in reality this happens only for As^{20}, while the other As coefficients have the same value within the error bars; ii) the coefficients for D-phases of the even cycles should be lower than those for odd ones; this is certainly true for D^{19} and D^{20}.

Our method of investigation seems to be less appropriate for the check of the CR-drift theory, while it should give indications on the type of interplanetary disturbances dominating the solar-cycle phase. From this point of view the correlation coefficient obtained for the D^{20} phase is accounted for by the prevalent presence, in the ecliptic plane, of corotating travelling disturbances connected with polar coronal holes. They have always a positive geomagnetic response in the planetary indices (e.g. Borello Filisetti et al., 1988 and references therein), while the associated CR-modulation phenomena are small (Iucci et al., 1979b). If the above is true, the capability of polar coronal holes to extend equatorialwards (and to generate long-lasting high-speed streams engulfing the ecliptic) would be the primary cause for the negligible values of correlation coefficients during the D-phases. Therefore, the coefficient for the D^{19}-phase would be explained in a natural way; there were very few (if any) solar-wind streams connected with polar- coronal holes during the solar-cycle N. 19 (see also Sect. 3). Moreover, the correlation coefficients obtained for the As-phases support the hypothesis of a prevalent presence of flare-related disturbances, in the heliospace, during the first part of each solar-activity cycle.

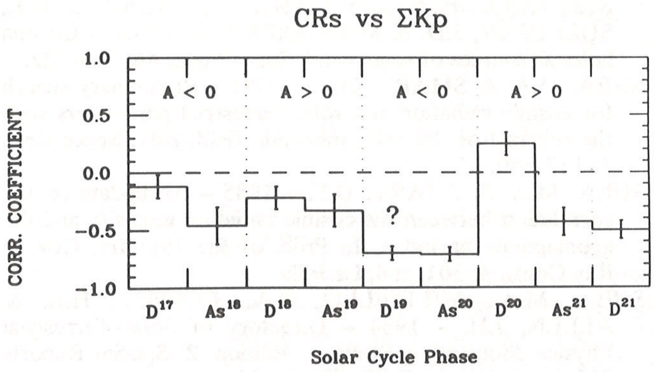

Figure 5. Correlation coefficients between the monthly CR intensity and the geomagnetic index ΣKp for time periods as in Fig. 3. The question mark in the descending phase D^{19} indicates the "unexpected" high value of correlation coefficient (see the text).

5. CONCLUSIONS

Preliminary results obtained through correlative analyses between monthly values of ΣKp-indices, Rz and CR intensities are presented for the period 1937-1986. It is suggested that the correlation coefficient of Rz vs. ΣKp (see Fig. 3) is: - practically the same (within error bars) for all the ascending phases considered; - anomalously higher for the descending phase of solar-activity cycle N. 19; in general, negligible correlation coefficients are obtained for the other descending phases. Most probably, during D^{19}-phase polar coronal holes were unable to cover (for a long time) low heliographic latitudes, preventing the associated corotating solar-wind streams to engulf the ecliptic plane; it follows that there is quite a good correlation between the transient solar-wind streams (as measured by Rz) and the geomagnetic activity level (as measured by ΣKp).

The results obtained by Shea & Smart (1981, 1985), supporting the Hale cycle effect predicted by the drift theory, may be explained also taking into account that polar coronal holes have covered negligible areas towards the helioequator during the D^{19}-phase and vast areas during the D^{20} phase.

The role of interplanetary disturbances (and of their sources) seems to be relevant in this type of analysis. Looking for the Hale cycle-related phenomena on galactic cosmic-ray behaviour this role must be taken into account.

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REFERENCES

BABCOCK, H.W. – 1961 – The topology of the suns's magnetic field and the 22-year cycle. Astrophys. J., **133**: 572-587.

BORELLO FILISETTI, O., LOVERA, G., MUSSINO, V., PARISI, M. & STORINI, M. – 1988 – On the geomagnetic response to high-speed solar-wind streams. Annales Geophysicae, **6**: 627-634.

BURLAGA, L.F. – 1975 – Interplanetary streams and their interaction with the Earth. Space Sci. Rev., **17**: 327-352.

DeVORE, C.R. & SHEELEY, N.R. – 1987 – Simulations of the sun's polar magnetic field during sunspot cycle 21. Solar Phys., **108**: 47-59.

DRYER, M. – 1974 – Interplanetary shock waves generated by solar flares. Space Sci. Rev., **15**: 403-468.

FILISETTI, O., LOVERA, G. & MUSSINO, V. – 1983 – Correlation of cosmic-ray intensity with geomagnetic Kp index and solar-magnetic-field reversal. Lettere al Nuovo Cimento, **37**: 312-314.

HALE, G.E. – 1913 – Preliminary results of an attempt to detect the general magnetic field of the sun. Astrophys. J., **38**: 27-98.

HALE, G.E. & NICHOLSON, S.B. – 1938 – Magnetic observations of sunspots, 1917-1924. Carnegie Inst. Publ. 498, Washington, D.C., 105 pp.

HARVEY, J.W. & SHEELEY, N.R. – 1979 – Coronal holes and solar magnetic fields. Space Sci. Rev., **23**: 139-158.

HUNDHAUSEN, A.J. – 1972a – Coronal Expansion and Solar Wind. Springer-Verlag, New York, 238 pp.

HUNDHAUSEN, A.J. – 1972b – Interplanetary shock waves and the structure of solar wind disturbances. In Solar Wind, NASA SP-308: 393-434, Asilomar.

HUNDHAUSEN, A.J. – 1981 – Coronal evolution during sunspot cycle: coronal holes observed with the Manua Loa K-Coronameters. J. Geophys. Res., **86**: 2079-2094.

IUCCI, N., PARISI, M., STORINI, M. & VILLORESI, G. – 1979a – Forbush decreases: origin and development in the interplanetary space. Il Nuovo Cimento, **2C**: 1-52.

IUCCI, N., PARISI, M., STORINI, M. & VILLORESI, G. – 1979b – High-speed solar-wind streams and galactic cosmic-ray modulation. Il Nuovo Cimento, **2C**: 421-438.

IUCCI, N., PARISI, M., STORINI, M. & VILLORESI, G. – 1984 – Interplanetary disturbances during Forbush decreases. Il Nuovo Cimento, **7C**: 467-488.

JOKIPII, J.R. – 1986 – Effects of three-dimensional heliospheric structures on cosmic ray modulation. In The Sun and the Heliosphere in Three Dimensions. (R.G. Marsden, ed.), D. Reidel Publ. Co., 375-387.

JOKIPII, J.R., LEVY, E.H. & HUBBARD, W.B. – 1977 – Effects of particle drift on cosmic-ray transport. I. General properties, application to solar modulation. Astrophys. J., **213**: 861-868.

KRIEGER, A.S., TIMOTHY, A.F. & ROELOF, E.C. – 1973

– A coronal hole and its identification as the source of a high velocity solar wind stream. Solar Phys., **29**: 505-525.
LANGE, I. & FORBUSH, S.E. – 1948 – Cosmic-ray results from Huancayo Observatory, Peru, June 1936-December, 1946, including summaries from Observatories at Cheltenham, Christchurch, and Godhavn, through 1946. Carnegie Inst. Publ. 175, XIV, 182 pp.
MARSDEN, R.G. (ed.) – 1986 – The Sun and the Heliosphere in Three Dimensions. D. Reidel Publ. Co., 525 pp.
MAYAUD, P.N. – 1972 – The aa indices: a 100-year series characterizing the magnetic activity. J. Geophys. Res., **77**: 6870-6874.
MAYAUD, P.N. – 1980 – Derivation, Meaning, and Use of Geomagnetic Indices. Geophysical Monograph **22**, American Geophysical Union, Washington, D.C., 154 pp.
McKIBBEN, R.B. – 1988 – Cosmic Ray Modulation. In Proc. Sixth Int. Solar Wind Conf. (V.J. Pizzo, T. Holzer & D.G. Sime, eds.), **2**: 615-633.
McKINNON, J.A. (revised by) – 1987 – Sunspot Numbers: 1610-1985 based on The sunspot-activity in the years 1610-1960. Report UAG-95, World Data Center A for Solar-Terrestrial Physics, Boulder, Colo., 112 pp.
NEUGEBAUER, M. (ed.) – 1983 – Solar Wind Five. NASA Conf. Publ., **2280**, 742 pp.
NEUPERT, W.M. & PIZZO, V. – 1974 – Solar coronal holes as sources of recurrent geomagnetic disturbances. J. Geophys. Res., **79**: 3701-3709.
NOLTE, J.T., KRIEGER, A.S., TIMOTHY, A.F., GOLD, R.E., ROELOF, E.C., VAIANA, A., LAZARUS, A.J., SULLIVAN, J.D. & McINTOSH, P.S. – 1976 – Corona holes as sources of solar wind. Solar Phys., **46**: 303-322.
SHEA, M.A. & SMART, D.F. – 1981 – Preliminary search for cosmic radiation and solar-terrestrial parameters with the reversal of the solar magnetic field. Adv. Space Res., **1**: 147-150.
SHEA, M.A. & SMART, D.F. – 1985 – An update on the correlation between the cosmic radiation intensity and the geomagnetic aa index. In Proc. of the 19th Int. Cosmic Ray Conf., **4**: 501-504, La Jolla.
SHEA, M.A., MILITELLO, S.A., COFFEY, H.E. & ALLEN, J.H. – 1984 – Directory of Solar-Terrestrial Physics Monitoring Stations. Edition 2. Special Reports 239, Hanscom A.F.B., Bedford, 474 pp.
STORINI, M. – 1990 – Cosmic-ray modulation and solar-terrestrial relationships. Il Nuovo Cimento, **13C**: 103-124.
WEBB, D.F., DAVIS, J.M. & McINTOSH, P.S. – 1984 – Observation of the reappearance of polar coronal holes and the reversal of the polar magnetic field. Solar Phys., **92**: 109-132.
WITHBROE, G.L. – 1986 – Origins of the solar wind in the corona. In The Sun and the Heliosphere in Three Dimension (R.G. Marsden, ed.), D. Reidel Publ. Co., 19-32.
ZIRKER, J. (ed.) – 1977 – Coronal holes and high-speed wind streams. Colorado Associated University Press, Boulder, Colo., 454 pp.

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