IL NUOVO CIMENTO VOL. 20 C, N. 6 Novembre-Dicembre 1997

Cosmic rays for solar-terrestrial physics (*)

M. STORINI

Reparto Raggi Cosmici - IFSI/CNR, c/o Dipartimento di Fisica
Università di Roma I "La Sapienza" - P.le A. Moro 2, I-00185 Roma, Italy

(ricevuto il 5 Dicembre 1996; approvato il 18 Marzo 1997)

Summary. — Aspects of the research program conducted over the 1991-94 period by the CNR/IFSI project on *Cosmic Rays in the Heliosphere* are reviewed. Recent findings related to the solar-interplanetary-terrestrial chain are discussed.

PACS 96.40 – Cosmic rays.
PACS 96.40.Cd – Interplanetary propagation and effects.
PACS 96.60.Vg – Particle radiation, solar wind.
PACS 01.30.Cc – Conference proceedings.

1. – Introduction

Research work over issues of Solar-Terrestrial Physics (STP) has grown remarkably in the last ten years. Several scientific enterprises have been undertaken to intensify interdisciplinary investigations. In this context, cosmic ray (CR) research should be a powerful tool for STP understanding. The fairly good coincidence between the sunspot cycle and the CR modulation cycle is known from the fifties [1] and medium- and long-term variabilities are under investigation from long time ago. Nowadays we are making efforts to:

i) evaluate the reliability of a 22-year cycle in CR modulation, *i.e.* even-odd sunspot cycle differences in the long-term behaviour;

ii) learn on induced coronal-hole effects along the solar-activity cycles;

iii) clarify CR observational features around the maximum phase of sunspot cycles, *i.e.* the *Gnevyshev gap* (see below) and related solar phenomena inducing a bimodal distribution of maximum CR modulation levels;

iv) estimate possible long-term variations in the solar-activity level and the corresponding responses in the heliosphere.

(*) Paper presented at the VII Cosmic Physics National Conference, Rimini, October 26-28, 1994.

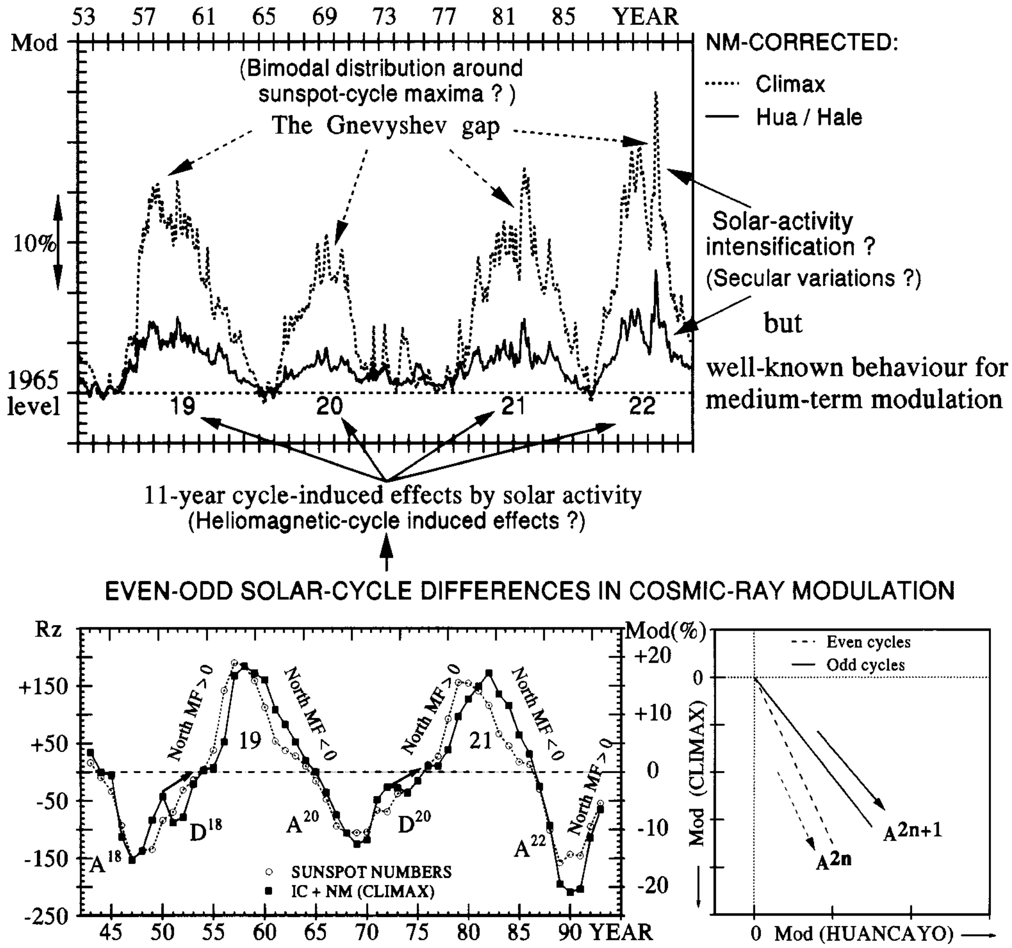

Fig. 1. – Aspects of the long-term cosmic-ray modulation (Mod) useful for forecasting work in Solar-Terrestrial Physics (see the text).

Here the importance of CR studies for the comprehension of some environmental problems and the STP forecasting duties is emphasized.

2. – Variability of galactic cosmic-ray intensity on long-term basis

The monthly averages of pressure-corrected data for Climax (N 39.4, W 106.2; height: 3400 m; cutoff rigidity: about 3 GV) and Huancayo (HUA: S 12.0, W 75.3; height: 3400 m; cutoff rigidity: about 13 GV; from 1992 on data from Haleakala (Hale) detector have been used to update the series) neutron monitors [2] are displayed, from January 1953 on, in the upper panel of fig. 1, where features currently under study have also been shown. The lower panel, instead, exemplifies findings connected with the above i) point. The right panel gives a sketch of the rigidity dependence of CR modulation during ascending phases of odd and even sunspot cycles, as inferred for cycles 19 to 22 by [1, 2]. The left panel illustrates yearly averages of CR modulation (Cheltenham/Fredericksburg ionization chambers + Climax neutron monitor; see [5] for details) and sunspot numbers (Rz). Negative (positive) values stand for even (odd) cycles. The polarity of the northern heliomagnetic field, MF, is reported together with the solar-activity phases for even cycles: A for ascending and D for descending phase. The CR recovery phase seems to be different during consecutive sunspot cycles, being it characterized by two steps (the second one marked by an arrow) during even cycles (see also [6]). Moreover, the analysis of data from polar-looking cosmic-ray detectors from 1965 to 1987 suggests a residual CR modulation of about 1% at the start of cycle 21 (see upper panel of fig. 1 reported by [7]), which is not present at the beginning of even sunspot cycles. However, the nearly unmodulated CR level is very often reached after the solar-activity maximum phase of cycle 20 (from the middle of 1971 on; lower panel of fig. 1 reported by [7]). If this behaviour is typical for even cycles, we may suppose that the transient activity during even D-phases is inhibited or reduced during the latter part of the CR recovery. Under this hypothesis, stable, wide and long-lived coronal holes dominate the physical conditions of the near-ecliptic environment (it was seen during cycle 20). Hence, due to the long survive of recurrent high-speed solar-wind streams and the associated macrostructures in the outer heliosphere, the CR incoming in the inner heliosphere is reduced. Finally, from fig. 1 (left lower panel) we observe that the odd CR modulation phases are always delayed to the Rz trend, irrespective of the A- or D-phase considered.

All these findings must be added to the well-known alternate triangular- and square-wave envelopes observed during the three most recent CR modulation cycles (*e.g.* [8] and references therein). There is another peculiar feature to be remarked during the CR modulation cycle. From the upper panel of fig. 1 it is evident that the maximum CR modulation levels avoid the maximum solar-activity phase and it happens in each cycle. We call this "valley" the *Gnevyshev gap*, because Gnevyshev found evidences that the Schwabe (the sunspot) cycle does not contain one but two macro waves of activity with different physical properties and that several solar-terrestrial parameters reflect them [7-12]. In other words, as concerns CR, it is expected that strong modulation phenomena peak before and after sunspot maxima, giving rise to a bimodal distribution of depleted CR intensities (generally with the first peak in the late A-phase and the second one in the early D-phase). We have checked the phenomenon on CR data with two different techniques [7, 13] and we conclude that the *Gnevyshev gap* is a real average feature also for the galactic CR modulation, while each peak contains a multiple structure related to the frequency and intensity of transient solar events. Work is in progress, by means of cross-correlation analyses between CR intensities and several solar-activity parameters, to identify proxy data sets for transient-induced effects on CR modulation [14, 15].

Finally, we add that the monthly data set reveals that the absolute maximum level of CR modulation was reached during the present cycle (June 1991), suggesting a probable intensification in the solar-activity level, in agreement with information coming from other solar-activity indices (see, for instance, [2, 16-21]).

It is beyond the scope of this paper to review progress in CR modulation theories (see [22] for a recent work) but we summarize in fig. 2 the "ingredients" currently used to simulate CR variability. We notice that some long-term features emerging from solar-activity parameters are very often missing. For example, latitudinal and hemispheric differences in the heliospheric physical conditions are seldom included. We will discuss on their possible role in the following.

'INGREDIENTS' FOR LONG-TERM COSMIC-RAY FEATURES

CONCEPTS

- Convection + diffusion + adiabatic energy changes;
- gradient and curvature drifts;
- tilt angle for heliospheric neutral sheet;
- magnetic helicity with adiabatic focusing.

VARIABILITY FOR — **3-DIMENSIONAL HELIOSPHERE**

- Heliospheric magnetic field;	
- interplanetary plasma;	
- solar-wind streams + interaction regions:	$\leq$ 5-10 UA
- merged interaction regions: (local, transient and/or corotating)	$\geq$ 5-10 UA
- global merged-interaction regions:	$\geq$ 10-20 UA
- heliospheric boundary	$\geq$ 45 UA. (probably > 100 UA)

Fig. 2. – Concepts used to investigate cosmic-ray propagation in the heliosphere.

3. – Getting an insight into the matter

The time lag between the CR modulation onset and the one of the sunspot cycle for even (18, 20, 22) and odd cycles (19, 21) has been definitively proved to be different: during odd cycles the CR modulation is more delayed, with a major time lag for low neutron-monitor energies (see [23, 24] and references therein). Looking at the half-yearly data of the green corona brightness (FeXIV 530.3 nm) during the years 1943-1993 we found:

– Evidences for a simultaneous onset-time of the green corona cycle in the equatorial (± 0–15 degrees) and middle-latitudinal (± 20–40 degrees) belts during even cycles, while in odd cycles the latter anticipates the former [23, 25, 26].

– A dissimilar coronal behaviour during odd and even rising phases. A nearly 22-year periodicity (Hale cycle?) is found for the middle-latitudinal belt (± 20–40 degrees) when the series of the absolute minimum values is considered. There is a clear peak in excess during odd cycles [23, 25, 27] and it correlates well with the long-term behaviour of other solar parameters [23, 28]. For example, the right panel of fig. 3 shows the difference between two consecutive 6 monthly averages of sunspot numbers (*Rz*, see [2, 29]) from cycle 1 to 22 (*i.e.* an estimate of the *Rz* derivative). We notice a dual-peak behaviour emerging in the final part of odd *A*-phases (reinforcement of *Rz*), which seems to be absent during the even ones at least for the cycles under study.

Moreover, except for cycles 4 and 8 (the even cycles close to the Dalton minimum in solar activity), the *Rz* peak for even cycles is always lower than the one attained in the following odd cycle (a 22-year cycle effect?). The left panel of fig. 3 (top) shows that this rule [30] is valid also for the hemispheric sunspot distribution (derived from [31]). How-

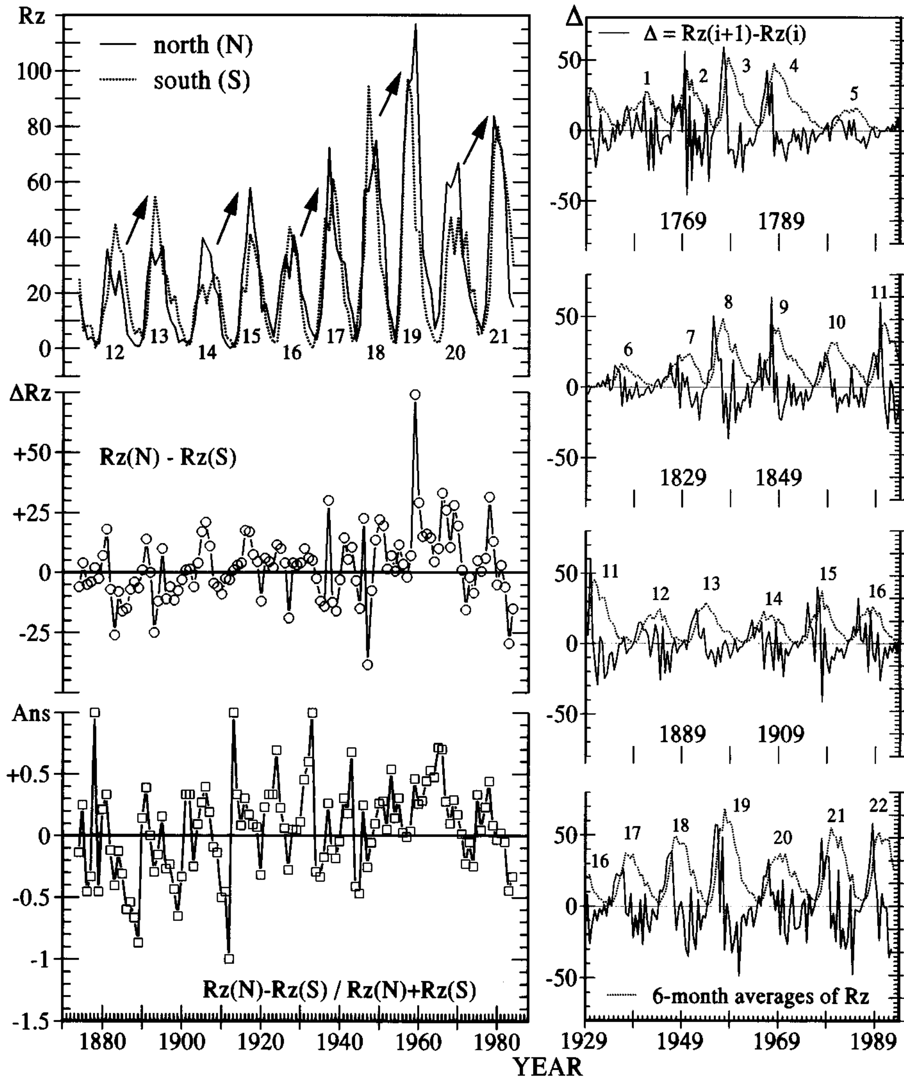

Fig. 3. – Left panel: hemispheric occurrence of sunspot numbers on annual basis (top) together with its difference (centre) and the north-south asymmetry (Ans, bottom), as derived from [30]. Right panel: long-term trends for the half-yearly averages of *Rz* (dotted line) and the difference between two consecutive values (solid line). Sunspot cycle numbers are shown in both panels.

ever, in several periods one hemisphere of the Sun appeared to be dominant (see middle and bottom panels). Hence, we checked in the green corona data if the hemispheric behaviour is the source of the even-odd cyclic trend described above. We found that for the five investigated cycles (18 to 22) the middle-latitude belt of the southern hemisphere is better involved in the trend than the northern one, in agreement with Swinson *et al.* results on an even-odd cyclic trend in sunspot parameters during A-phases [32].

There is also a strong possibility that the repetitive patterns of the even-odd recovery phases of CR modulation derived from low neutron monitor energies (fig. 1, left lower

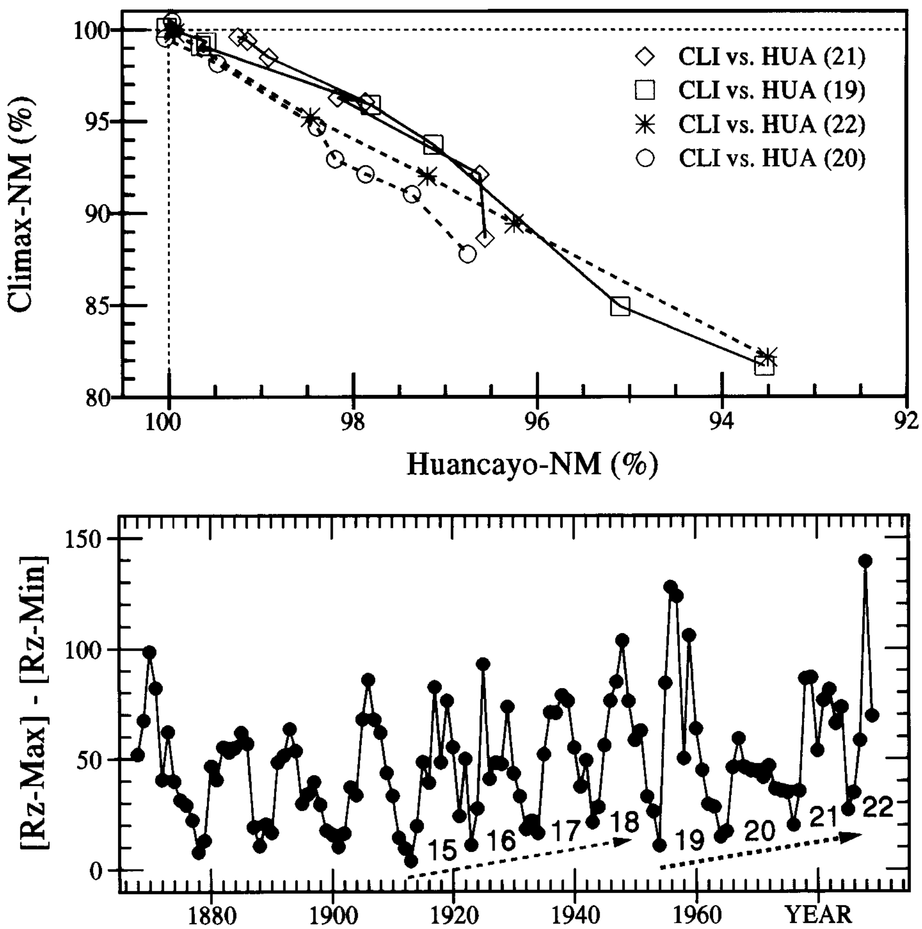

Fig. 4. – Upper panel: regression plot, based on half-year values, of Climax neutron monitor (CLI) intensity decrease *vs.* Huancayo neutron monitor (HUA) intensity decrease during ascending solar-activity phases 19 to 22. Lower panel: difference in the extreme values of the average monthly Rz found in each year from 1868 to 1989.

panel) are related to a different heliolatitudinal-dependent control of the interplanetary medium during consecutive sunspot cycles. A preliminary study shows that the second step observed in Climax data during even cycles is also present at high neutron-monitor energies: *e.g.* Huancayo data [5]. However, during odd cycles, the second recovery step for Huancayo could not be excluded, at least for the middle part of the D-phase. Perhaps, during odd cycles, stable, wide and long-lasting coronal holes are missing in the low heliolatitudes but are present in the middle ones with the associated solar wind incapable to engulf the near-ecliptic region. This hypothesis seems to be supported by observational coronal-hole data [33, 34].

Certainly, our findings (*i.e.* the possibility that the middle heliolatitudinal belt could be a key source for discrepancies in the long-term CR behaviour) should be viewed as a preliminary step into a clarification of the long-term heliolatitudinal control of the heliospheric space (see also [35, 36]). However, we believe that some progress has been achieved using the sunspot number as a primary proxy index for transient solar activity.

We remark another long-term *Rz* feature that could be relevant in the understanding of secular variations of STP parameters. If the extreme monthly averages are selected in each year and the difference between them (*Rz*-dif) is computed, a new data series is obtained to evaluate the *Rz* cyclic variability. The new cycles are reported in the lower panel of fig. 4. From sunspot cycle 15 on there is an increasing base-line level for the *Rz*-dif cycle (*i.e.* evaluated from one cycle to the next): it stops at the beginning of cycle 19, and again repeats from cycle 19 to 22 (another signature for a solar-activity intensification during the second half of our century?). Being this effect related to *Rz*, we believe that traces of this cyclic behaviour, if any, could be found during A-phases. The upper panel of fig. 4 (to compare with the right lower panel of fig 1) gives the regression plot between half-yearly averages of CR modulation at Climax and Huancayo: the rigidity dependence of galactic CRs is indeed different during odd and even rising phases but the end-points for A^{20} and A^{21} are similar, while data points for A^{22} leave those for A^{20} to reach the ones of A^{19}. This could be a reason for the parametric analogies ascribed to cycles 19 and 22 and remarked by several authors (see, for instance, [37]). Indeed, CR data for A-phases suggest a cyclicity longer than two sunspot cycles. It will be interesting to check solar-terrestrial parameters at the beginning of cycle 23.

The reader's attention is drawn to the possibility that superimposed on the well-known periodicities (Schwabe and Hale cycles) there is a much longer cycle of unknown properties. We recall, as examples, the Gleissberg Cycle of about 90 years found in the long-term envelope of sunspot data and/or the 55-Year Grand Cycle discussed by Yoshimura [38]. On the other hand, solar physicists often invoke an extended solar-activity cycle of about 17 years, but with the available solar data it is not easy to explain our findings.

4. – Induced responses in the terrestrial environment

Parallel to the search of oustanding features in the long-term trend of galactic CR intensities, we looked for possible associated signatures in the terrestrial environment. STP covers a large number of research fields. We restricted ourselves to the geomagnetic activity level and the ozone issue.

When the long-term trend of the average monthly aa-index (now available back to July 1844, see *e.g.* [39] and references therein) is investigated in terms of the A- and the D-phase of sunspot cycles, the linear correlation coefficient (r) between aa and *Rz* (on monthly basis) indicates that:

– r is always positive for A-phases but not for D-phases, supporting differences between both phases as obtained with CR data.

– The r-indices for even A-phases are all similar within error bars.

– The r-index for odd A-phases alternates from low ($r < 0.5$, during sunspot cycle number $4n + 1$, with $n = 2, \ldots$) to high ($r > 0.5$, during sunspot cycle number $4n + 3$, with $n = 2, \ldots$) values, in agreement with a 55-Year Grand Cycle. In fact, the r-index time history for A-phases suggests an r-periodicity of about 5 cycles (see fig. 4 reported by [39]).

– The r-index time history for D-phases is compatible with a periodicity of about 8 cycles (the Gleissberg Cycle). We have presented evidences that the long-term variability in the coronal hole features could be responsible for this secular trend [40]. In other words, there is a better *liaison* between the transient solar activity and the geomagnetic activity level during the rising phase than in the declining phase of each sunspot cycle.

Moreover, it is well known that together with a dual-peak distribution of intense geomagnetic levels (*e.g.* [40-42] and references therein) there exists an increasing baseline level for the aa-index during the current century. We believe that it comes out from changes in solar features and related outputs. Probably the heliospheric magnetic-field variability is more involved in the phenomenon than the solar-wind speed [43].

The ozone layer in the terrestrial environment acts as a filter reducing the intensity of harmful wavelengths reaching the Earth's surface. Available data indicate a long-term ozone depletion in the high-latitude atmosphere. Man-made chlorofluorocarbon production is supposed to be the source of the chemical and dynamical processes involved. However, if we analyze the monthly dataset of the ozone density over the South Pole (1962-1992 data set [44]) and we select the measured ozone density minima in each year, we recognize fairly well signatures of the solar activity [45, 46]. For example, during each *Gnevyshev gap* a relative minimum (or "valley") is observed and the claimed strong depletion of the atmospheric ozone content starts with the interplanetary magnetic-field intensification (*i.e.* during the eighties). A mechanism linking geomagnetic phenomena to the atmospheric ozone should not be excluded. An evaluation of the energy transfered from the solar wind to the magnetosphere supports this connection for cycles 20 and 21 [45,47]. Unfortunately, relevant gaps in solar-wind parameters do not allow a detailed study including sunspot cycle 22, but CRs indicate that it is a very active cycle. From a geomagnetic index such as the Ap one, we found that the average change in the geomagnetic activity level during the A^{19} was similar to the one of A^{22}. We noticed that also the ozone density minima at South Pole during the *Gnevyshev gap* of cycle 22 was similar to the one reported for the 1958 springtime at Dumont d'Urville [28, 45, 48] (we recall the A^{19} and A^{22} features described in the previous section). One may assert that the ozone production/destruction mechanism is very complex and the role of solar-induced effects via geomagnetic perturbations could not be relevant. However, the study of the ozone variability during three single geomagnetic events suggests that:

– the auroral belt could be involved in the ozone depletion phenomenon [45, 48, 49],

– not all the interplanetary perturbations could have a response in the ozone layer [50],

– There exists a solar-wind speed cut-off to prime effects on the terrestrial ozone dynamics [46].

5. – Conclusions

Although results here reported give support to the idea of well-defined behaviours in solar-terrestrial parameters over consecutive sunspot cycles, more detailed investigations are needed to distinguish between fact and fiction. We are only beginning to learn that there are several typical features along the solar-activity cycle enabling a more precise forecasting of STP concerns. A careful disentangle of solar-induced variations from the terrestrial-induced ones is required. We need a detailed data analysis of individual events, followed by the study of cumulative effects on the long-term trend of terrestrial parameters. We recall that, among the different datasets available to quantify the physical status of the interplanetary medium the one of the CR flux deserves a relevant role, as these charged particles are probes of the heliosphere. In particular, the continuous monitoring of CR intensities allows us to identify the tipology of the interplanetary perturbations overtaking the Earth [8], and to evaluate the terrestrial response to them. CR detectors should be maintained at work for more solar-activity cycles (we are collaborating with the Chilean network of CR detectors to improve the Antarctic Laboratory for Cosmic Rays: LARC station [51, 52]). These data will facilitate the understanding of past variability in solar-terrestrial parameters and the STP forecast work.

* * *

This paper partly covers an invited talk to GIFCO94. Thanks are due to coworkers and their institutions: Astronomical Institute of Tatranská Lomnica (Slovakia), Astronomical Institute of the Wroclaw University (Poland), La Sapienza University of Rome (Italy), Finnish Meteorological Institute (Helsinki - Finland), "Politecnico" of Turin (Italy), University of Chile (Santiago - Chile), University of "Magallanes" (Punta Arenas - Chile). Some topics of this research project were supported by ASI (1992-93), CNR/SAV agreement (1992-94) and the PNRA/MURST (1992-94).

REFERENCES

[1] FORBUSH S. E., *J. Geophys. Res.*, **59** (1954) 525.
[2] *Solar Geophysical Data*, NOAA, U.S. Dept. of Commerce (Boulder), Monthly Reports.
[3] POPIELAWSKA B. and SIMPSON J. A., in *Physics of the Outer Heliosphere*, edited by S. GRZEDZIELSKI and D. E. PAGE (Pergamon Press) 1990, p. 133.
[4] POPIELAWSKA B., *Planet. Space Sci.*, **40** (1992) 811.
[5] STORINI M., *Adv. Space Res.*, **16** (9) (1995) 51.
[6] AHLUWALIA H. S., *J. Geophys. Res.*, **99** (1994) 11561.
[7] STORINI M. and PASE S., *STEP GBRSC News*, **5** Special Issue (1995) 255.
[8] STORINI M., *Nuovo Cimento C*, **13** (1990) 103; **14** (1991) 211 (Erratum).
[9] GNEVYSHEV M. N., *Sov. Astron.-AJ*, **7** (1963) 311.
[10] GNEVYSHEV M. N., *Sov. Astron.-AJ*, **9** (1965) 387.
[11] GNEVYSHEV M. N., *Solar Phys.*, **1** (1967) 107.
[12] GNEVYSHEV M. N., *Solar Phys.*, **51** (1977) 175.
[13] SÝKORA J. and STORINI S., to be published in *J. Geomagn. Geoelectron.*
[14] ANTALOVÁ A., JAKIMIEC M. and STORINI M., in *The 8th International Symposium on Solar Terrestrial Physics, dedicated to STEP*, Part I (SCOSTEP, Sendai) 1994, p. 53.
[15] STORINI M., ANTALOVÁ A., and JAKIMIEC M., *J. Geomagn. Geoelectron.*, **47** (1995) 1085.
[16] SLAVIN J. A., JUNGMAN G. and SMITH E. J., *J. Geophys. Res.*, **13** (1986) 513.
[17] HARVEY A. K., in *Proceedings of the Workshop on the Solar Electromagnetic Radiation Study for Solar Cycle 22*, edited by R. F. DONNELLY (Springfield) 1992, p. 113.
[18] SMITH E. J., *Adv. Space Res.*, **16** (9) (1995) 153.
[19] HOEGY W. R., PESNELL W. D., WOODS T. N. and ROTTMAN G. J., *Geophys. Res. Lett.*, **20** (1993) 1335.
[20] SÝKORA J., MINAROVJECH M., BAVASSANO B., STORINI M. and PARISI M., in *Poster Papers Presented at the Seventh European Meeting on Solar Physics*, edited by G. BELVEDER, M. RODONÓ, B. SCHMIEDER and G. M. SIMNETT (Catania Astrophysical Observatory, Special Publication 1994), p. 31.
[21] STORINI M. and FELICI A., *Nuovo Cimento C*, **17** (1994) 697.
[22] POTGIETER M. S., in *Proc. XXIII ICRC, Invited, Rapporteur & Highlight Papers*, edited by D. A. LEAHY, R. B. HICKS and D. VENKATESAN (World Scientific Publishing Co.) 1994, p. 213.
[23] STORINI M., BORELLO FILISETTI O., MUSSINO V., PARISI M., and SÝKORA J., *Solar Phys.*, **157** (1995) 375.
[24] NYMMIK R. A. and SUSLOV A. A., *Adv. Space Res.*, **16** (9) (1995) 217.

[25] STORINI M., SÝKORA J., FELICI A., BAVASSANO B. and PARISI P., in *Proceedings of IAU Colloquium No. 144 on Solar Coronal Structures*, edited by V. RUŠIN, P. HEINZEL and J.-C. VIAL (VEDA Publ. Co., Bratislava) 1994, p. 143.
[26] STORINI M. and SÝKORA J., this issue, p. 923.
[27] STORINI M. and SÝKORA J., *Contr. Astron. Obs. Skalnaté Pleso*, **25** (1995) 90.
[28] STORINI M., *SETP GBRSC News*, **5**, Special Issue (1995) 267.
[29] MCKINNON J. A., *Report UAG-95*, WDC A for Solar-Terrestrial Physics (Boulder, CO) 1987.
[30] GNEVYSHEV M. N. and OHL A. I., *Astron. Zh.*, **25** (1948) 18.
[31] MURAYAMA T. and NOSAKA T., *Planet. Space Sci.*, **39** (1991) 751.
[32] SWINSON D. B., KOYAMA H. and SAITO T., *Solar Phys.*, **106** (1986) 35.
[33] WANG Y.-M. and SHEELEY N. R. Jr., *Astrophys. J.*, **355** (1990) 726.
[34] BRAVO S. and STEWART G., *Solar Phys.* **154** (1994) 377.
[35] BAVASSANO B., STORINI M., FELICI A., PARISI M. and SÝKORA J., in *Solar-Terrestrial Energy Program, The Initial Results from STEP Facilities and Theory Campaigns*, COSPAR Colloquia Series **5**, edited by D. N. BAKER, V. O. PAPITASHVILI and M. J. TEAGUE (Elsevier, Oxford) 1994, p. 285.
[36] SÝKORA J., BAVASSANO B., STORINI M. and PARISI M., in *Solar-Terrestrial Energy Program, The Initial Results from STEP Facilities and Theory Campaigns*, COSPAR Colloquia Series **5**, edited by D. N. BAKER, V. O. PAPITASHVILI and M.J. TEAGUE (Elsevier, Oxford) 1994, p. 289.
[37] AHLUWALIA H. S., *Planet. Space Sci.*, **40** (1992) 1227.
[38] YOSHIMURA H., *Astrophys. J.*, **227** (1979) 1047.
[39] MUSSINO V., BORELLO FILISETTI O., STORINI M. and NEVANLINA H., *Ann. Geophys.*, **12** (1994) 1065.
[40] BORELLO FILISETTI O., MUSSINO V., PARISI M. and STORINI M., *Ann. Geophys.*, **10** (1992) 668.
[41] GONZALEZ W. D., GONZALEZ A. L. C. and TSURUTANI B. T., *Planet. Space Sci.*, **38** (1990) 181.
[42] CLÚA DE GONZALEZ A. L., GONZALEZ W. D., DUTRA S. L. G. and TSURUTANI B. T., *J. Geophys. Res.*, **98** (1993) 9215.
[43] FEYNMAN J. and CROOKER N. U., *Nature*, **275** (1978) 626.
[44] KOMHYR W. D., private communication (1993).
[45] DE PETRIS M., GERVASI M., MORENO G., PARISI M. and STORINI M., *Trends Geophys. Res.*, **2** (1993) 459.
[46] STORINI M., ALTO A., MORENO G. and PARISI M., *Proceedings of the 8th International Symposium on Solar-Terrestrial Physics, dedicated to STEP*, Part-I (SCOSTEP, Sendai) 1994, p. 227.
[47] DE PETRIS M., GERVASI M., MASI S., MELCHIORRI OLIVO B., MORENO G., PARISI M. and STORINI M., *Ann. Geophys.*, **9** (1991) 381.
[48] RIGAUD P. and LEROY B., *Ann. Geophys.*, 8 (1990) 791.
[49] DE PETRIS M., GERVASI M., MASI S., MELCHIORRI OLIVO B., MORENO G., STORINI M. and CALISSE P., *Ann. Geophys.*, 8 (1990) 541.
[50] STORINI M., MARCUCCI M. F., ORSINI S. and CANDIDI M., *Report CNR/IFSI-95-8*, (Frascati) 1995.
[51] CORDARO E. G. and STORINI M., *Nuovo Cimento C*, **15** (1992) 539.
[52] STORINI M. and CORDARO E. G., *IV Workshop Italian Research on Antarctic Atmosphere* (*Porano, October 21-23, 1991*), edited by M. COLACINO, G. GIOVANELLI and L. STEFANUTTI, *SIF Conf. Proc.*, Vol. **35** (Editrice Compositori, Bologna) 1992, p. 233.