The solar and interplanetary causes of space storms in solar cycle 23

V. Bothmer, EU-INTAS-ESA Team of Project 99-727, *Member, IEEE*

***Abstract*— This paper presents a brief overview on the results of a joint EU-INTAS-ESA project which is focused on the investigation of the interplanetary and solar causes of geomagnetic storms in solar cycle 23. Based on the in situ data of the solar wind plasma and magnetic field parameters measured by the Wind and ACE (Advanced Composition Explorer) spacecraft in joint analysis with the unprecedented set of remote sensing observations provided by the SOHO (Solar and Heliospheric Observatory) satellite since its launch in December 1995, the main statistical results from the detailed investigation of geomagnetic disturbed days with Ap>20 are presented here.**

***Index Terms*— Space measurements, space phenomena, space weather, coronal mass ejections.**

I. INTRODUCTION

Major geomagnetic storms are caused by solar wind structures that possess strong (>> 5 nT) southward components of the interplanetary magnetic field at 1 AU and usually, but not always higher wind speeds than average [1, 2]. Coronal mass ejections (CMEs) are a prime source of geomagnetic storms because they lead to the most intense values of –Bz and V at 1 AU followed by co-rotating interaction regions and Alfvenic fluctuations at times of enhanced solar wind speed within coronal hole flows [1, 2, 3, 4, 5, 6, 7, 8]. The interplanetary counterparts of CMEs can trigger geomagnetic storms basically in two different ways or in combinations of these two ways: 1. through their specific internal magnetic field configuration in case the CMEs exhibit the internal structure of helical magnetic flux ropes (commonly called magnetic clouds) - not only by SN or NS rotations, but also through the cloud's axis orientation when it is highly inclined and possessing a southward field direction; 2. through draping of the ambient interplanetary magnetic field (IMF) in case they drive fast shock waves ahead [4].

Despite, this clear view of the solar and interplanetary sources of major geomagnetic storms, the picture is less clear at lower levels of geomagnetic activity because of the possible contributions of several different sources (CMEs with lower values of –Bz and V, coronal hole flows (fast streams), heliospheric current sheet crossings, etc.). Another aspect is our lack in our understanding of the solar cycle variations of these sources.

For the current solar cycle 23 a unique set of simultaneous spacecraft measurements of the solar wind at 1 AU from the IMP-8, Wind and ACE (Advanced Composition Explorer) satellites [5, 6, 7, 8] together with unique remote sensing observations from the SOHO (SOlar and Heliospheric Observatory) spacecraft [9] allows to investigate the solar and interplanetary causes of geomagnetic storms in unprecedented detail.

In a joint EU/ESA-INTAS project we have analyzed all interplanetary causes and solar sources of geomagnetic disturbances with Ap>20 (Kp > 3+) during the years 1997-2001, i.e. during the rise and maximum of solar cycle 23. Additionally the ring storm parameter D_{ST} has been conveyed. The statistical properties of Ap in this cycle have been described already in [15]. Here we present an overview of the results of this study, primarily focusing on the implications of the interplanetary data.

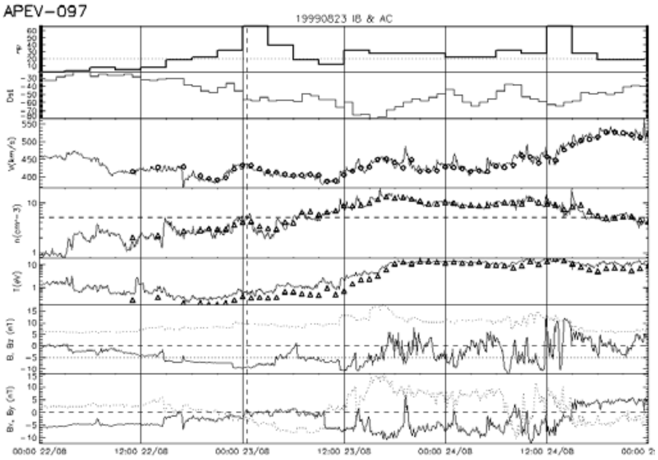
II. INVESTIGATION OF GEOMAGNETIC STORMS

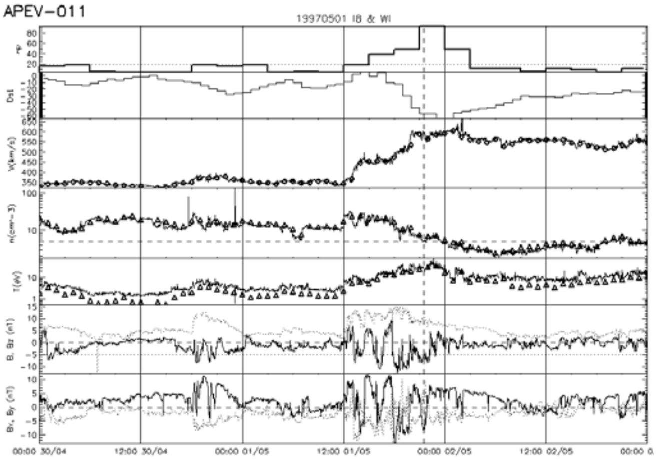
Concerning the classification of geomagnetic activity we follow the classification of the Sunspot Index Data Center with: a) Active Periods with 20 < Ap < 30 (3+ < Kp < 4+), minor storms with 30 < Ap < 50 (4+ < Kp < 5+), major storms with 50 < Ap < 100 (5+ < Kp < 7) and severe storms with Ap > 100 (Kp ≥ 7). In order to study the solar and interplanetary causes of these active and stormy periods in the present solar cycle, we compiled an event list (http://dec1.npi.msu.su/apev) including all 255 days with Ap>20 during 1997-2001 based on the Ap-data provided by the National Geophysical Data Center (NGDC) at Boulder, CO, USA (http://www.ngdc.noaa.gov/stp/). Additionally, running averages of Ap were considered as well as Ap*-values provided by NGDC (http://www.ngdc.noaa.gov/stp/ GEOMAG/apstar.shtml), but it was found that the differences are negligible for the statistics.

Manuscript received November 3, 2003; revised April 2, 2004. This work was carried out under EU-INTAS-ESA project 99-727.

V. Bothmer is with the Max-Planck-Institut für Aeronomie, D-37191 Katlenburg-Lindau, Germany(e-mail: bothmer@linmpi.mpg.de).

The EU-INTAS-ESA Team 99-727 consists of I. S. Veselovsky and A. V. Dmitriev and A.N. Zhukov being with Institute of Nuclear Physics, Moscow State University, Moscow 119992, Russia, E. P. Romashets being with Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave, Department of Magnetism of the Earth and Planets, Sector of Space Magnetoplasma Dynamics IZMIRAN, Troitsk, Moscow Region 142190, Russia, P. J. Cargill being with Imperial College of Science, Technology and Medicine, London, SW7, 2BZ,UK. A. N. Zhukov is now with Royal Observatory of Belgium, Avenue Circulaire 3, B–1180 Brussels, Belgium.





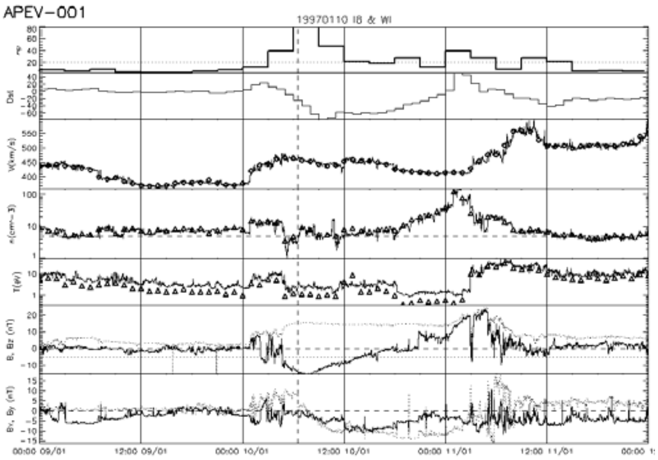
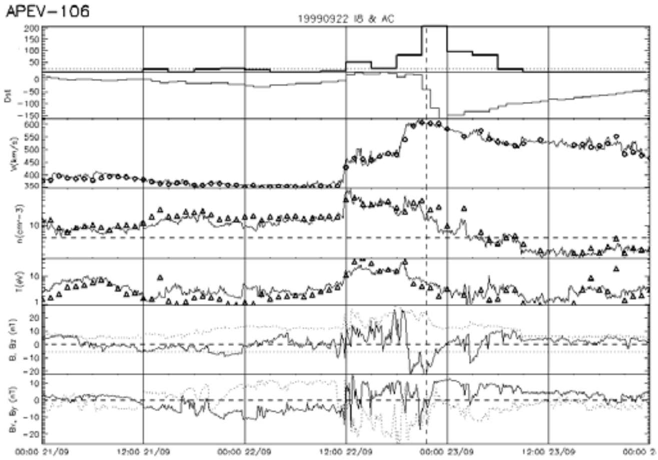


Figure 1a-c. Each plot shows geomagnetic (ap, D_{St}) and interplanetary (solar wind speed V, Proton Density n, Temperature T, Magnetic Field Magnitude B and Cartesian components Bz, Bx, By (dotted)) data for three different causes of geomagnetic disturbed days with Ap>20. Top panel: Mild activity caused by turbulent slow wind near the HCS, middle panel: CIR including compressed Alfvenic fluctuations followed by the CH flow, bottom panel: CME/CIR interaction.

For each disturbed day we have studied the interplanetary parameters in GSM (Geocentric Solar Magnetospheric) coordinates as measured by the Wind and ACE satellites in



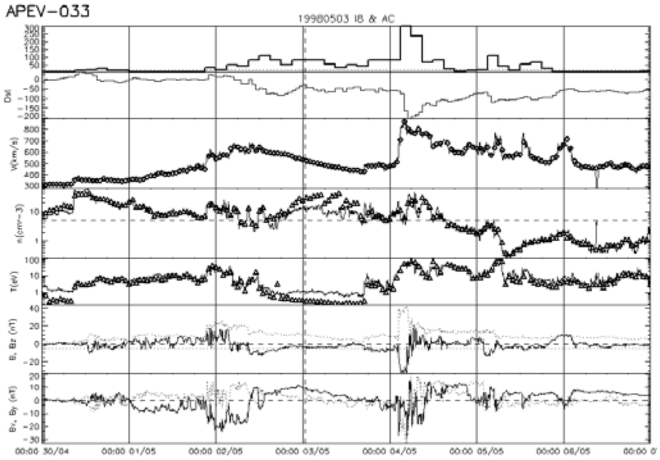


Figure 1 d-e. Same parameters as in Fig. 1a-c. Top panel: A CME in the solar wind at 1 AU causing a geomagnetic storm through draping of the IMF ahead of it, bottom panel: Two interacting CMEs in the solar wind.

correlation with observations from SOHO. The study of the solar source regions has been described partially already in [15, 16].

The number of Ap-events was 185, being less than the number of disturbed days because each event can span time periods longer than a day, e.g., in case of shock associated CMEs of typical sizes of 0.25 AU at 1 AU (e.g., [12] or times spent in high speed coronal hole flows, see examples presented). From the inspection of the interplanetary data plots (provided at http://dec1.npi.msu.su/apev) we have identified the interplanetary characteristics for each Ap-event. Note that the data were inspected in detail by using the three-hourly ap-values for better investigation of the details in each event (see Fig. 1a-e).

Basically, the Ap-events, ranging from very minor geomagnetic activity levels (e.g., Ap event APEV-097) up to major geomagnetic storms (e.g., APEV-106), could be classified according to five different types of interplanetary/solar causes, shown in Figure 1 a)-e):

1. Slow wind near the heliospheric current sheet associated with low levels of geomagnetic activity (commonly Ap<30, see Figure 1a).
2. Corotating Interaction Regions (CIRs) followed by Coronal hole (CH) plasma flows (commonly Ap<60, Figure 1b).
3. Interplanetary counterparts of CMEs interacting with CIRs (Ap<150, Figure 1c).
4. The draping of the interplanetary magnetic field (IMF) ahead of CMEs in the solar wind or its internal magnetic field configuration (or both) (Ap<170, Figure 1d,e).
5. Multiple interacting interplanetary counterparts of CMEs (Ap<200, Figure 3).

Cause of Storm	Number of Ap>20 days	Number of events	Common Ap-Range
Slow wind	8	8	<30
CIR/CH	90	55	<60
CME/CIR	18	11	<150
CME	101	81	<170
MCMEs	38	30	<200
Total Number	255	185	

Table 1. Causes of geomagnetic storms during 1997-2001. Acronyms: CIR (co-rotating interaction region), CH (coronal hole), CME (coronal mass ejection), MCMEs (multiple CMEs).

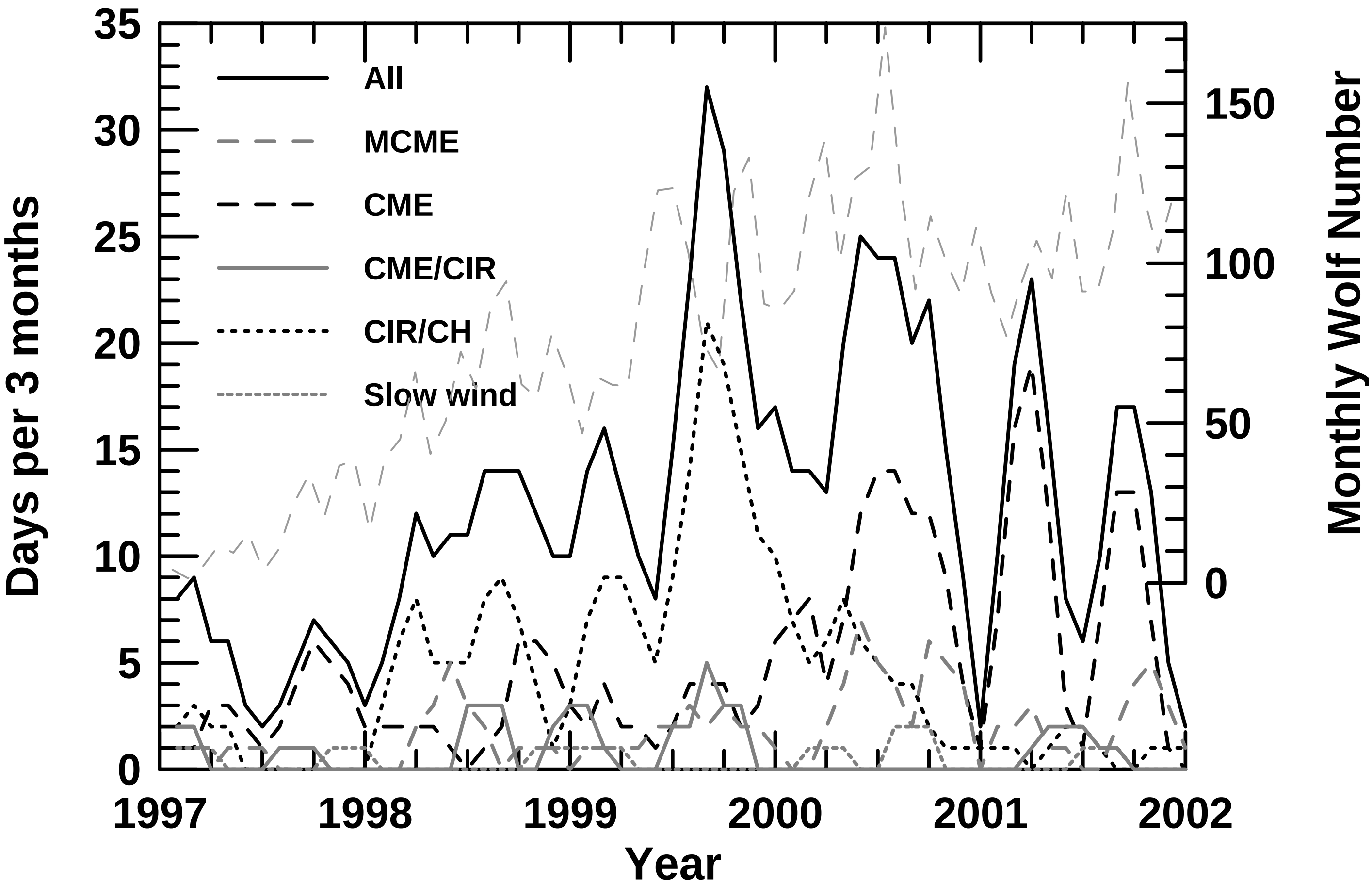
The frequency for each of the above listed causes as being responsible for a geomagnetic event with Ap>20 during 1997-2001 is listed in Table 1. Most days were disturbed by plasma flows from coronal holes and by counterparts of CMEs, including multiple CMEs. So far cycle 23 was moderate in terms of the sunspot number and with respect to the level of individual space storms, but it is well known that major storms also often occur in the declining phases of the solar activity cycles.

Figure 2 presents 1-month running (1-month step) number of Ap-disturbed days per 3 months (3 month-window) from 1997 until end of 2001 for the number of disturbed days together with the individual sources of the storms. This way of averaging was used because to keep seasonal effects visible and to apply meaningful statistics. There are no any other averages, except for the smoothed sunspot number.

Most disturbed days occurred in mid 1999, 2000 and 2001. Whereas in mid 1999 still many storms, although they were of lower activity, were caused by CHs, this picture dramatically changed in 2000 when geomagnetic activity was starting to become completely CME dominated. It was well known that CHs and associated CIRs play a major role for geomagnetic storms in the decreasing phase of solar activity, but the role of these features in the rising phase of the cycle was so far underestimated.

The time variation of the solar/interplanetary sources of activity will be of importance when seasonal variations are considered, which is beyond the scope of the present study.

Figure 2. Frequency distribution of the different sources of geomagnetic storms with Ap>20 from 1997-2001 in comparison with the sunspot number.



III. CONCLUSION

Based on a systematic study of the solar wind data for all geomagnetic storms with Ap>20 from 1997 until the end of 2001 we found that geomagnetic activity (storms) basically are caused by a) turbulence in slow wind streams, b) CH flows with associated CIRs, c) CME/CIR interactions, d) CMEs, e) MCMEs.

Whereas up to mid 1999 many geomagnetic storms of low level were caused by CH flows, from early on in 2000 CMEs started completely dominating geomagnetic activity and the average level of geomagnetic storms increased. It will be interesting to compare these results in more detail in subsequent studies with previous results on the long-term behaviour of geomagnetic activity [18, 19, 20, 21, 22, 23, 24].

However it should be pointed out that severe geomagnetic storms can generally occur at any time of the cycle.

ACKNOWLEDGEMENT

The project has been carried out under INTAS grant 99-00727. The study is connected also with the scientific investigations of the project Stereo/Corona, supported by the German „Bundesministerium für Bildung und Forschung" through the „Deutsches Zentrum für Luft- und Raumfahrt e.V." (DLR) under project number 50 OC 0005. Stereo/Corona is a science and hardware contribution to the optical imaging package SECCHI currently being developed for the NASA STEREO mission to be launched in 2005. VB likes to thank Alexey Dmitriev and Andrei Zhukov for providing the interplanetary data plots and for establishing Fig. 3. We also like to thank the two anonymous referees for their helpful comments.

REFERENCES

[1] B. Tsurutani, "The Interplanetary Causes of Magnetic Storms, Substorms and Geomagnetic Quiet", in Space Storms and Space Weather Hazards, 103-130, I.A. Daglis (ed.), Kluwer Academic Publishers, 2001.

[2] V. Bothmer and R. Schwenn, "The solar and interplanetary causes of major geomagnetic storms", *J. of Geomagn. and Geoelectr*., 47, 1127-1132, 1995.

[3] V. Bothmer, "Solar Corona, Solar Wind Structure and Solar Particle Events", Proc. of ESA Workshop on Space Weather Nov. 1998, ESA WPP-155, ISSN 1022-6656, 117-126, 1999.

[4] Burlaga, L.F., R.P. Lepping, The causes of recurrent geomagnetic storms, Planet. Space Phys., 25, 1151, 1977.

[5] Burlaga, L.F., K.W. Behannon, L.W. Klein, Compound streams, magnetic clouds and major geomagnetic storms, J. Geophys. Res., 92, 5725, 1987.

[6] Gosling, J.T., S.J. Bame, D.J. McComas, J.L. Phillips, Coronal mass ejections and large geomagnetic storms, Geophys. Res. Lett., 127, 901, 1990.

[7] Gosling, J.T., D.J. McComas, J.L. Phillips, S.J. Bame, Geomagnetic activity associated with Earth passage of interplanetary shock disturbances and coronal mass ejections, J. Geophys. Res., 96, 7831, 1991.

[8] Tsurutani, B.T., W.D. Gonzalez, The interplanetary causes of magnetic storms: A review, AGU Geophys. Monogr., 98, 77-89, 1997.

[9] V. Bothmer, Sources of Magnetic Helicity Over the Solar Cycle, Proc.. ISCS 2003 Symposium, 'Solar Variability as an Input to the Earth's Environment', Tatranska Lomnica, Slovakia, 23-28 June 2003, ESA SP-535, 419-427, 2003.

[10] K.W. Ogilvie, et al., SWE, "A comprehensive plasma instrument for the Wind spacecraft: The Global Geospace Mission", *Space Sci. Rev*., 71, 55-57, 1995.

[11] R.P. Lepping, et al., "The Wind magnetic field investigation: The Global Geospace Mission, *Space Sci. Rev*.", 71, 207-229, 1995.

[12] D.J. McComas, Bame, S.J., Barker, P., Feldman, W.C., Phillips, J.L., Riley, P., Griffee, J.W., "Solar Wind Electron Proton Alpha Monitor (SWEPAM) for the Advanced Composition Explorer", *Space Sci. Rev*., 86, 563-612, 1998.

[13] C.W. Smith, L'Heureux, J., Ness, N.F., Acuna, M.H., Burlaga, L.F., Scheifele, J., "The ACE magnetic field experiment", *Space Sci. Rev*., 86, 613, 1998.

[14] B. Fleck, Domingo, V., Poland, A.I., Eds.: *The SOHO mission*, Solar Phys., 162, No. 1,2. Reprinted by Boston: Kluwer Academic Publishers, 1995.

[15] V. Bothmer, I. S. Veselovsky, A. V. Dmitriev, A. N. Zhukov, P. Cargill, E. P. Romashets, and O. S. Yakovchouk, "Solar and Heliospheric Causes of Geomagnetic Perturbations during the Growth Phase of Solar Cycle 23", Solar System Research, Vol. 36, No. 6, 2002, pp. 499–506. Translated from Astronomicheskii Vestnik, Vol. 36, No. 6, 2002, pp. 539–547.Original Russian Text Copyright © 2002 by Bothmer, Veselovskii, Dmitriev, Zhukov, Cargill, Romashets, Yakovchuk.

[16] A.N. Zhukov, I.S. Veselovsky, F. Clette, J.-F. Hochedez, A.V. Dmitriev, E.P. Romashets, V. Bothmer, and P. Cargill, "Solar Wind Disturbances and Their Sources in the EUV Solar Corona", In: SOLAR WIND TEN: Proceedings of the Tenth International Solar Wind Conference, Pisa, Italy, 17-21 June 2002. Eds.: Marco Velli, Roberto Bruno, Francesco Malara. AIP Conference Proceedings - September 2, 2003 - Volume 679, Issue 1, pp. 711-714.

[17] V. Bothmer and R. Schwenn, "The Structure and Origin of Magnetic Clouds in the Solar Wind", *Annales Geophysicae*, 16, 1-24, 1998.

[18] Vilmer, N., M. Pick, R. Schwenn, P. Ballatore, J.P. Villain, On the solar origin of interplanetary disturbances observed in the vicinity of the Earth, Ann. Geophys., 21, 1-16, 2003.

[19] Richardson, I.G., H.V. Cane, Sources of geomagnetic activity during nearly three solar cycles (1972-2000), J. Geophys. Res., 107, A8, 10.1029/2001JA000504, 2002.

[20] Richardson, I.G., E.W. Cliver, H.V. Cane, Sources of geomagnetic storms for solar minimum and maximum conditions during 1972-2000, Geophys. Res. Lett., 28, 13, 2569-2572, 2001.

[21] Schreiber, H., On the periodic variations of geomagnetic acvtivity indices Ap and ap, Ann. Geophys. 16, 510-517, 1998.

[22] Gonzalez, A.L.C., W.D. Gonzalez, S.L.G. Dutra, B.T. Tsurutani, Periodic variation in the geomagnetic activity: a study based on the Ap Index, J. Geophys. Res., 98, 9215-9231, 1993.

[23] Gonzalez, W.D., A.L.C. Gonzalez, B.T. Tsurutani, Dualpeak solar cycle distribution of intense geomagnetic storms, Planet. Space Sci., 38, 181-187, 1990.

[24] Green, C.A., The semiannual variation in the magnetic activity indices Aa and Ap, Planet. Space Sci., 32, 297-305, 1984.