CME VELOCITIES, ACCELERATIONS, WIDTHS AND POSITIONS IN THE ASCENDING PHASE OF THE SOLAR CYCLE 23 (1996-2001)

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ABSTRACT/RESUME

An analysis of the coronal mass ejections (CMEs) during the ascending phase of solar cycle 23 (1996-2001) is performed; we study velocities, accelerations, widths and heliocentric latitude of emergence (position angle), their variation with time, as well as possible interdependences among them. The data set comes from the observations of CMEs by the SOHO LASCO C2 or C3 coronographs. An increase of the average CME velocity is found from solar minimum to solar maximum. The average acceleration however remains close to zero through the observation period, yet the standard deviation of the distribution of CME accelerations increases as the CME "ejection rate" increases with increasing solar activity. The average width is almost constant, while its standard deviation increases drastically.

1. DATA ANALYSIS AND RESULTS

The CME study is of great importance because they play a fundamental role in the interplanetary medium and in the development of space weather [2-11]. We study the CME during the ascending phase of solar cycle 23 (1996-2001), using the CME catalogue of SOHO observations by the Large Angle Spectroscopic Coronagraph (LASCO)[1] generated and maintained by the Center for Solar Physics and Space Weather.

We examine the time behaviour and possible relations between estimated apparent CME velocities (fig 1), accelerations (fig 2), widths (fig 3) and positions (fig 4a and b) while in fig. 5 the distribution of CME positions shows their tendency to take off near the equator (±45^o).

Four different estimates of the CME velocities (available in the database) have been used in this analysis: (a) linear fit of the height-time evolution of the CME, (b) second order fit of the initial velocity, (c) second order fit of the final velocity and (d) velocities at 20 R_{Sun} for every CME. All average CME velocities, i.e. linear and second order fits, both for initial and

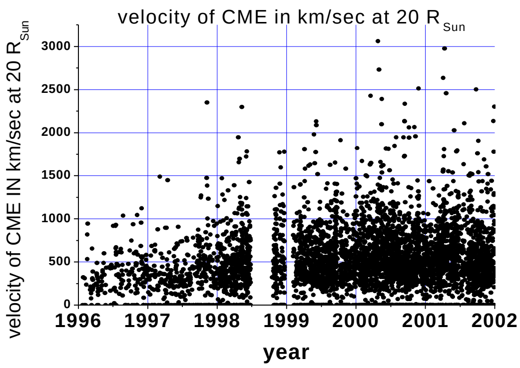

Fig 1 Velocities of CMEs vs. time

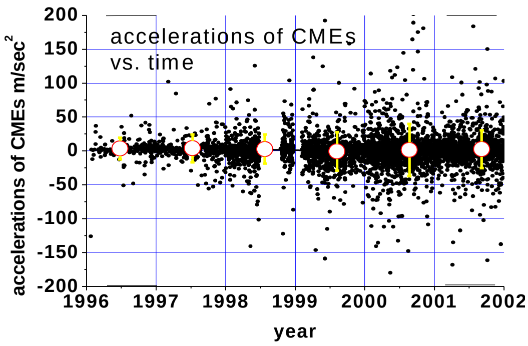

Fig 2 Accelerations of CMEs with time
Mean acceleration (open circles) is zero

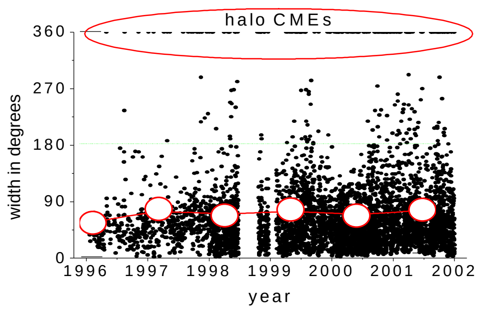

Fig 3 Width of CMEs vs time. Large open circles represent mean width over one year

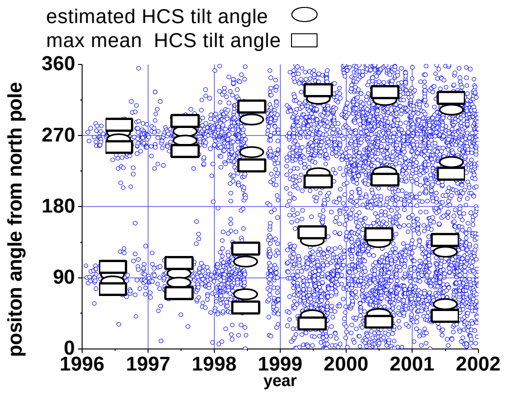

Fig 4a CME positions vs time.
Notice that near the minimum CMEs appear near the solar equator, while later at all heliolatitudes. The extend of CMEs appearance follows the maximum mean tilt of the heliospheric current sheet (HCS)

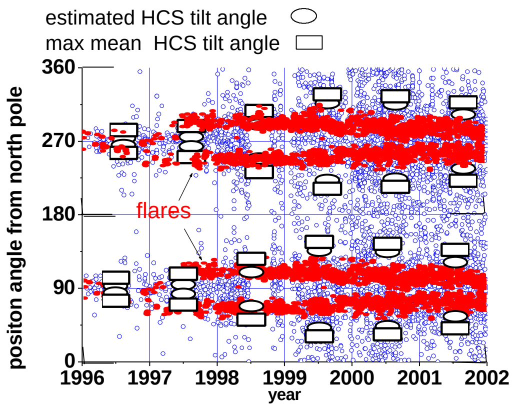

Fig 4b CME positions and flares vs time.
Notice that flares follow the *butterfly diagram*, i.e. gradually their average position approaches the equator from minimum to maximum, while the CMEs spread towards the poles, following the extend of the heliospheric current sheet (HCS)

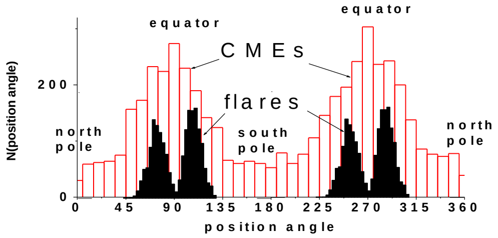

Fig 5 Distribution of CMEs and flares in position angle. It is evident that the CME maxima coincide with the equator, ±45^o and the flare distributions coincide with the latitudes of the sunspots (butterfly diagram), with maxima at latitude 20^o.

final velocity, as well as at 20 R_{Sun}) increase with time

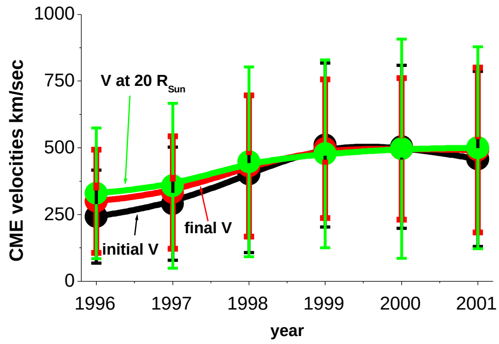

Fig 6 Time evolution of the CME velocities, averaged over one year. Notice that the average velocity increases substantially from minimum to maximum (almost double)

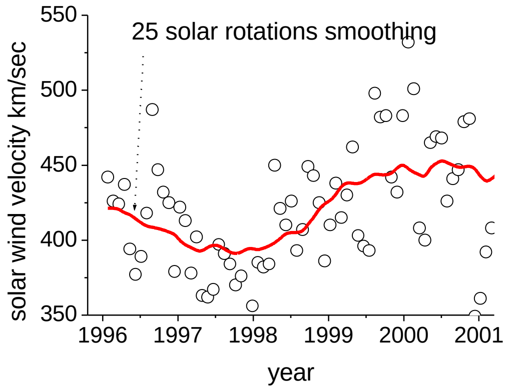

Fig 7 Solar wind velocity averaged over 27 days measured at 1AU. From minimum to maximum of solar activity shows a small increase

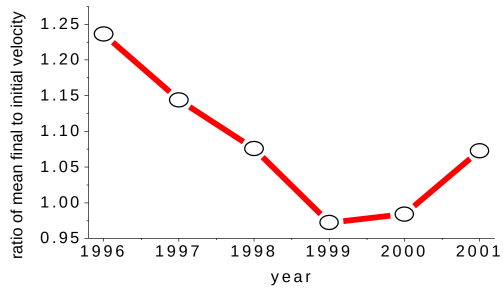

Fig 8 Time evolution of the ratio of mean final to initial CME velocity. Notice that the ratio reaches a minimum at the time all CME velocities reach their maximum value

approaching the solar maximum.

In 1996 the average velocities are about 250 to 330 km/sec reach a maximum of 500 km/sec in 1999 and retain this value afterwards. We have calculated the average values of CME velocities, accelerations and widths. The average CME velocities (fig 6) increase substantially (between 70% and 100%) from solar minimum towards the solar maximum. This change manifest itself in three years (1996 to 1999), well before the maximum. The solar wind velocity measured by IMP and ACE shows a small increase in 1998-1999 (fig 7). The ratio of mean final to mean initial CME velocity reaches a minimum at the time all CME velocities reach their maximum value (1999), as shown in fig 8. At the same time period (1996 to 2001) neither the solar wind flux (nV_{sw}), nor the solar wind pressure (nV_{sw}^2) shows any systematic change with time from minimum to maximum of solar activity. The standard deviations of all solar wind parameters show substantial changes during this time period.

Scatter plots of individual CME accelerations and velocities (initial, final and at 20 R_{Sun}) are presented in fig 9 to 12. Fig 9 shows that there is a clear velocity lower limit at 20 R_{Sun} for accelerated CMEs, while there is no lower limit for the decelerated ones. In a log-log scatter plot (fig 10, for accelerated CMEs only) the slope of the lower limit line is -1/2, while the slope of a possible upper limit line is -1/4. The lower limit line with slope -1/2 represents CMEs accelerated with constant acceleration during all their flight. Scatter plots of accelerations with initial and final velocities (fig 11 and 12) shows that very fast CMEs get decelerated after their take off, while slow CMEs accelerate during their flight. Solar wind possibly decelerates some fast CMEs, which could then develop a forward shock wave in front of them, but we can not speculate for the acceleration of the slow ones.

Neither the average widths nor the average accelerations show any changes with time. Yet the standard deviation of each year accelerations double after 1997.

The CME position evolution with time (fig 4a and b) shows that near the solar minimum CMEs have the tendency to start near the solar equator. Near the solar maximum CMEs appear more or less at all heliographic latitudes. This probably reflects the average extend of the polar coronal holes and possibly the inclination of the solar magnetic equator. Distribution of CME appearance with position angle for every year shows narrower distribution close to the solar equator near the minimum of solar activity and widens approaching the solar maximum. The appearance of CMEs near the poles might be related to dynamic pressure difference caused by the fast solar wind, which comes from the poles. Such a pressure difference might explain the spread of CMEs inside the polar coronal holes and the appearance near the poles.

Comparison of CME positions and flares for all this time period (fig 5

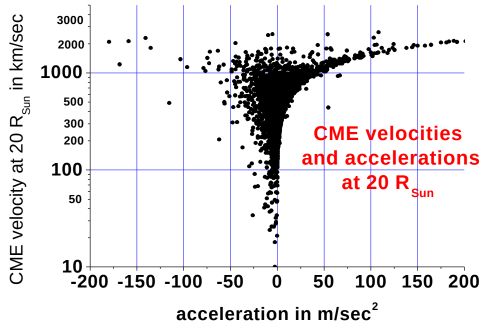

Fig 9 Scatter plot of accelerations and velocities of CMEs at 20 R_{Sun} .

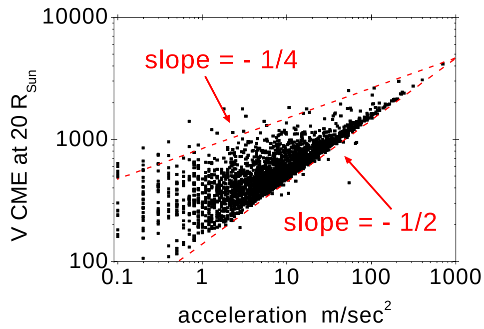

Fig 10 Scatter plot of accelerations and velocities of CMEs at 20 R_{Sun} .

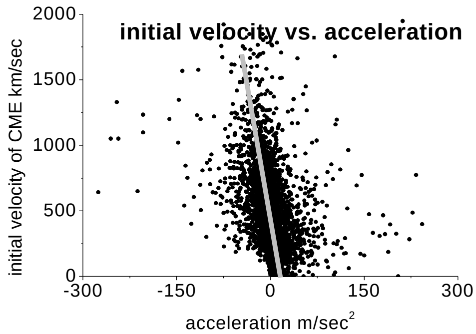

Fig 11 Initial velocity vs. acceleration

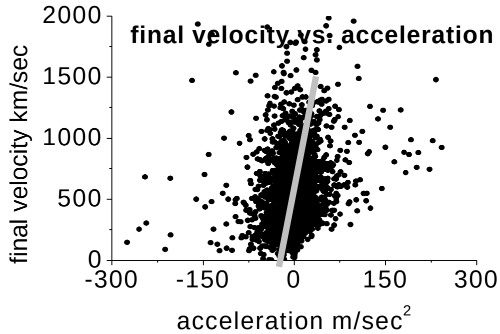

Fig 12 Final velocity vs. acceleration

4b and 5) shows that flares follow the *butterfly diagram*, i.e. gradually their average position approaches the equator (from minimum to mxaimum), while the CMEs spread towards the poles, possibly following the extend of the heliospheric current sheet. This result perhaps reflects a lack of flare CME relation in some cases.

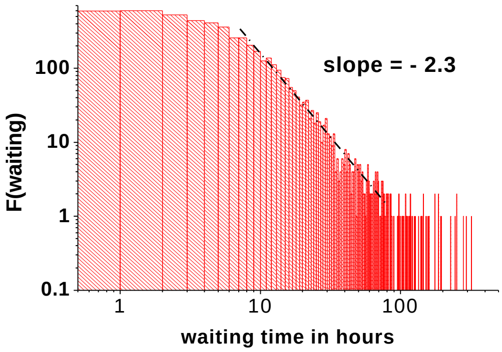

Fig 13 Distribution of waiting times between CME onsets

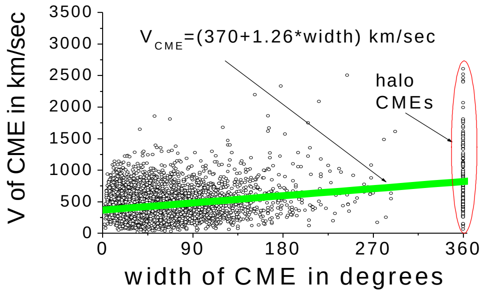

Fig 14 Scatter plot of CME velocities and widths. Linear fit shows strong relation

We have also studied the waiting time of CMEs, i.e.the time between consecutive CMEs which shows that in a log-log diagram it has a slope of -2.3 (fig 13). Scatter plot of CME velocities and widths shows large spread, while linear fit shows strong relation between them (fig 14). Acceleration of the CME shows no dependence upon their width.

ACKNOWLEDGEMENTS:

We thank the University of Athens for providing the Grant 70/4/2469 for Space Physics. We would like also to thank Dr St. Cyr and the SOHO team for the CME catalogue The CME catalog is generated and maintained by the Center for Solar Physics and Space Weather, The Catholic University of America in cooperation with the Naval Research Laboratory and NASA. SOHO is a project of international cooperation between ESA and NASA. This CME Catalog has been compiled by Drs Seiji Yashiro, Grzegorz Michalek and Dr Nat Gopalswamy to whom we express our thanks. We also express our gratitude to Dr Todd Hoeksema for the heliospheric current sheet inclination data.

REFERENCES

1. Brueckner, G.E., R.A. Howard, M.J. Koomen, C.M. Korendyke, D.J. Michels, J.D. Moses, D.G. Socker, K.P. Dere, P.L. Lamy, A. Llebaria, M.V. Bout, R. Schwenn, G.M. Simnett, D.K. Bedford, and C.J. Eyles, The large angle spectroscopic coronagraph (LASCO), *SOLAR PHYSICS*, 162, 357-402, 1995
2. Hundhausen, A.J., *Coronal mass ejections, in THE MANY FACES OF THE SUN*, edited by K.T. Strong, J.L.R. Saba, B.M. Haisch, and J.T. Schmelz, Springer-Verlag, New York, 143-200, 1999.
3. Hundhausen, A.J., Sizes and locations of coronal mass ejections: SMM observations from 1980 and 1984-1989, *J. GEOPHYS. RES.*, 98, 13,177-13,200, 1993.
4. Hundhausen, A.J., C.B. Sawyer, L. House, R.M.E. Illing, and W.J. Wagner, Coronal mass ejections observed during the Solar Maximum Mission: Latitude distribution and rate of occurrence, *J. GEOPHYS. RES.*, 89, 2,639-2,646, 1984.
5. Hundhausen, A.J., J.T. Burkepile, O.C. St.Cyr, Speeds of coronal mass ejections: SMM observations from 1980 and 1984-1989, *J. GEOPHYS. RES.*, 99, 6543-6552, 1994.
6. St.Cyr, O.C. and A.J. Hundhausen, *On the interpretation of "halo" coronal mass ejections*, in PROCEEDINGS OF THE SIXTH INTERNATIONAL SOLAR WIND CONFERENCE, eds V.J. Pizzo, T.E. Holzer, and D.G. Sime, NCAR/TN-306+Proc, 1987.
7. St.Cyr, O.C., and D.F. Webb, Activity associated with coronal mass ejections at solar minimum: SMM observations from 1984-1986, *SOLAR PHYSICS*, 136, 379- 394, 1991.
8. St.Cyr, O.C., and R.A. Howard, SOHO LASCO measurements of CME expansion, *EOS*, 80, F816, 1999.
9. St.Cyr, O.C. et al *A comparison of ground-based and spacecraft observations of coronal mass ejections from 1980-1989, J. GEOPHYS. RES.*, 104, 12,492-12,506, 1999.
10. St.Cyr O. C.et al *Properties of LASCO CMEs, J. GEOPHYS. RES*. 105, 18169-18185, 2000
11. Leblanc, Y. et al, *Tracing shock waves from the corona to 1 AU: Type II radio emission and relationship with CMEs, JOURNAL OF GEOPHYSICAL RESEARCH, 106*, 25301-25312, 2001