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Statistical Study of the Geoeffectivity of Halo Coronal Mass Ejections Associated with X-Class Flares during Solar Cycles 23 and 24

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Abstract

By analysing a long series of data (1996-2019), we show that solar cycle 23 was more marked by violent solar flares and coronal mass ejections (CMEs) compared to solar cycle 24. In particular, the halo coronal mass ejections associated with X-class flares appear to be among the most energetic events in solar activity given the size of the flares, the speed of the CMEs and the intense geomagnetic storms they produce. Out of eighty-six (86) X-class halo CMEs, thirty-seven (37) or 43% are highly geoeffective; twenty-four (24) or approximately 28% are moderately geoeffective and twenty-five (25) or 29% are not geoeffective. Over the two solar cycles (1996 to 2019), 71% of storms were geoeffective and 29% were not. For solar cycle 23, about 78% of storms were geoeffective, while for solar cycle 24, about 56% were geoeffective. For the statistical study based on speed, 85 halo CMEs associated with X-class flares were selected because the CME of 6 December 2006 has no recorded speed value. For both solar cycles, 75.29% of the halo CMEs associated with X-class flares have a speed greater than 1000 km/s. The study showed that 42.18% of halo (X) CMEs with speeds above 1000 km/s could cause intense geomagnetic disturbances. These results show the contribution (in terms of speed) of each class of halo (X) CMEs to the perturbation of the Earth's magnetic field. Coronal mass ejections then become one of the key indicators of solar activity, especially as they affect the Earth.

Keywords

CME Halo (X), Geoeffectivity, Geomagnetic Storm, Solar Flare, Solar Cycle

1. Introduction

Halo coronal mass ejections associated with X-class flares (Halo X CMEs) are very energetic solar events that can cause major magnetic disturbances on Earth, with direct consequences for our current technological systems. It is therefore essential to have a good understanding of solar activity in order to anticipate these events and their consequences for the Earth's environment.

The characteristics of coronal mass ejections, such as their speed and the class of flare with which they are associated, are crucial to understand how CMEs can affect the Earth's magnetosphere. High-energy CMEs are capable of causing large magnetic perturbations due to the magnetic energy, magnetic force pressure and north-south direction of the interplanetary magnetic field Bz that they carry.

Previous studies [1] [2] [3] have been carried out on the geoeffectivity of coronal mass ejections but for different periods that do not fully encompass the two solar cycles 23 and 24.

Our work involves a statistical study of the Halo coronal mass ejections associated with X-class flares and their geoffectivity, and a comparison of all the intense magnetic storms and those associated with Halo CMEs linked to X-class flares over the two solar cycles 23 and 24.

2. Data and Methodology

For this analysis, we use data on halo CMEs because halos are truly high-energy events with an average speed > 1000 km/s compared to 470 km/s for ordinary CMEs and are, on average, associated with major eruptions [1]. The data are taken from the SOHO /LASCO catalogue: https://cdaw.gsfc.nasa.gov/CME_list/halo for a period (1996-2019) covering solar cycles 23 and 24. Each CME halo is associated with its solar source (or not), its speed and the size of the associated soft X-ray flares. Informations on intense solar flares and associated active regions have been obtained from the spaceweatherlive data archive (https://www.spaceweatherlive.com/fr/activite-solaire). We use data from the International Geomagnetic Index Service (http://isgi.unistra.fr/data_download.php) to identify all intense geomagnetic storms over the period 1996-2019.

We identified intense solar events in satellite databases:

1) We have isolated all the intense (X-class) solar flares associated with Halo CMEs according to the characteristics given by the National Oceanic and Atmospheric Administration (NOAA). In this case, we considered all eruptions in the X1 to X28 class (forces R3 to R5). Between 1996 and 2019, we counted a total of 86 intense solar flares, including 59 X-class flares associated with CME halos in cycle 23 and 27 in cycle 24, all associated with CMEs directed or partially directed towards the Earth.

2) We found the Disturbance storm time (Dst) value corresponding to each CME halo (X) in order to determine the geoeffectivity based on the identification method described by [1]: we chose an average arrival window for CMEs of 4

days, starting the day after the CME date and ending after 4 days (CME date + 5 days). The minimum value of the Dst index in this time interval after the CME halo is attributed to this CME halo. In addition, when a period had multiple Dst minima, we arbitrarily assigned them to a single storm event if the minima were less than 24 hours apart, rather than defining each minimum as a separate storm.

3) The Dst index values collected are used to identify and represent the days on which intense geomagnetic disturbances (Dst ≤ −100 nT) occur during the periods 1996 to 2019. To do this, we selected all the intense geomagnetic disturbances between 1996 and 2019 and chose the smallest daily Dst value without taking into account the number of intense storms produced during the day. We therefore counted 115 intense geomagnetic storms (Dst ≤ −100 nT) that occurred during this period.

3. Results

3.1. Geoeffectivity of Halos Coronal Mass Ejections Associated with X-Class Flares

The ability of a CME to disrupt the magnetosphere through the generation of a magnetic storm is called geoeffectivity. It is measured in terms of geomagnetic indices such as Disturbance Storm Time (Dst). According to the minimum value of the Dst [1], Geomagnetic storms can be classified into five groups:

1) Weak (−30 to −50 nT), 2) Moderate (−50 to −100 nT), 3) Strong (−100 to −200 nT), 4) Severe (−200 to −350 nT), 5) Super (<−350 nT).

Halo CME followed by Dst ≤ −50 nT are considered geoeffective. Halos followed by Dst ≤ −100 nT are strongly geoeffective, while those followed by −50 nT ≤ Dst < −100 nT are moderately geoeffective.

It is usual to consider all Dst values ≤ −100 nT as being intense geomagnetic storms.

Of the 86 CMEs associated with X-class flares, thirty-seven (37) or 43% are strongly geoeffective; twenty-four (24) or about 28% are moderately geoeffective and twenty-five (25) or 29% are non-geoeffective.

Over the two solar cycles, about 71% of the storms were geoeffective and 29% were not.

Table 1 below shows the percentage of CME halos per solar cycle which are geoeffective and which are not geoeffective.

Table 1. Percentage of coronal mass ejections halos per solar cycle which are geoeffective and which are not geoeffective.

	Solar cycle 23	Solar cycle 24
Number of CME halos associated with X-class flares	59	27
Percentage of Geoeffective CMEs	≈78%	≈56%
Percentage of CMEs which are not geoeffective	**≈22%**	**≈44%**

3.2. Statistical Study of Halo Coronal Mass Ejections Associated with X-Class Flares and Intense Geomagnetic Storms during Solar Cycles 23 and 24

During sunspot cycle 23, the number of halo CMEs associated with X-class flares was highest in 2000 and 2001 (two years of maximum) and in 2005 (one year of the descending phase). For solar cycle 24, this number reached a remarkable peak in 2013 (a year of the maximum phase).

The profiles of the sunspot number Rz and the number of CME halos associated with X-class flares from 1996 to 2019 are shown in Figure 1.

The profiles for the sunspot number and the number of intense geomagnetic storms are shown in Figure 2. These curves show some remarkable peaks in solar cycle 23: 1998 (one year of the ascending phase), 2000, 2001, 2002 (three years of the maximum phase).

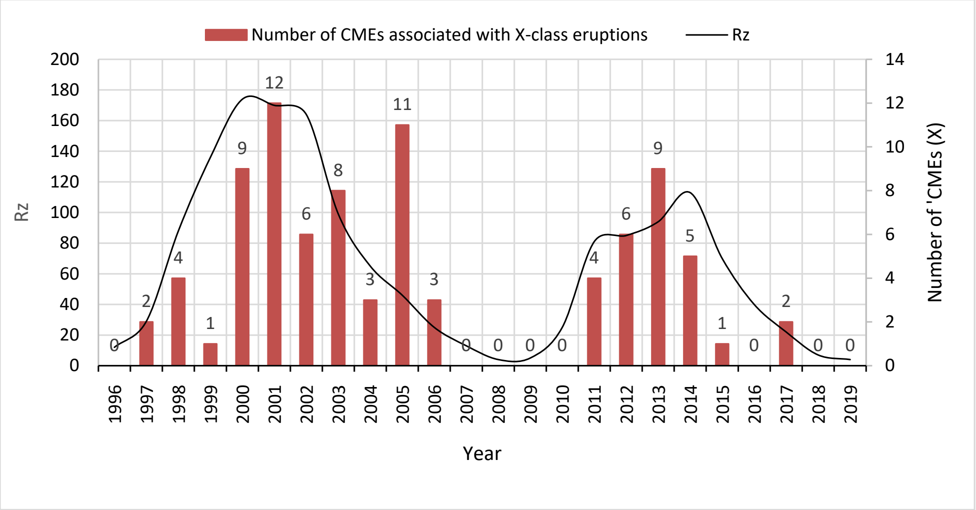

Figure 1. Profiles of the sunspot number Rz and the number of CMEs halos spots associated with X-class flares from 1996 to 2019.

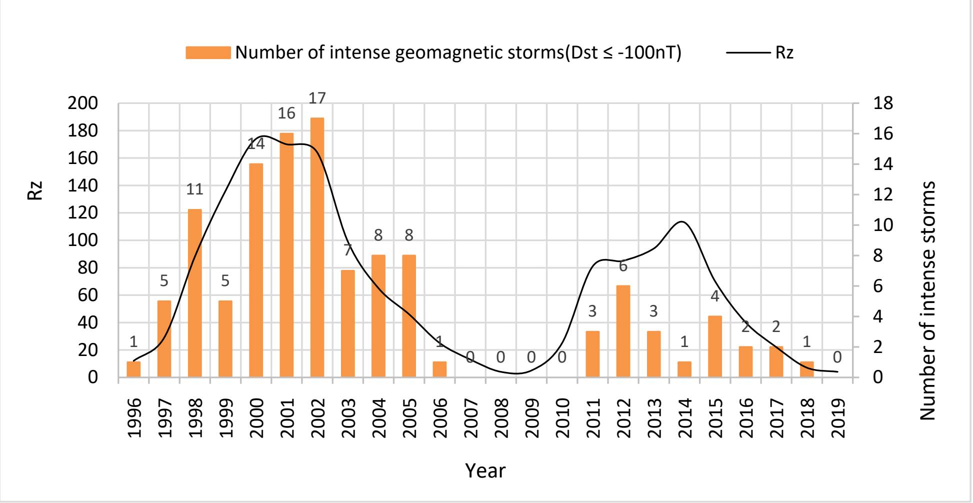

Figure 2. Profiles for the sunspot number and the number of intense geomagnetic storms.

For solar cycle 24, we noticed a remarkable decrease in the number of intense storms compared with cycle 23. No storms with Dst values ≤ −250 nT were observed during cycle 24, whereas such storms were present in the previous cycle.

It should be noted that the solar cycle 24 is characterised by its low sunspot rate, and also by its low number of intense geomagnetic storms.

Figure 3 shows the distribution of days with severe disturbances (these days correspond to days with intense geomagnetic storms, Dst ≤ −100 nT, a total of 115 intense geomagnetic storms) and severe disturbances days caused by CME halos (X) (a total of 27) during the periods 1996-2019. For the number of severe disturbances days by halo CMEs associated with X-class flares, we chose the smallest daily Dst value without taking into account the number of intense storms produced during the day.

During solar cycle 23, only eight years record days disrupted by CMEs (X). In terms of the number of days disturbed by CME halos (X), 2001 was the most disturbed year in this cycle.

Remarkably, 2002, the year with the most days of severe disturbances, had no CME (X)-related days.

For solar cycle 24, there are only two years with severe CME(X) disturbances : 2011 and 2012.

Table 2 summarises the number of halo CMEs associated with X-class flares and the number and percentage of intense geomagnetic disturbances (Dst ≤ −100 nT) they produced during solar cycles 23 and 24.

Figure 4 shows the speed profiles of the 85 halo CMEs associated with X-class flares (one of the 86 is not classified due to missing speed values) and the associated magnetic disturbances.

Statistical analysis shows that 64 out of 85 halo CMEs (X) have a speed greater than 1000 km/s and 27 out of 64 are associated with a Dst value of less than −100 nT.

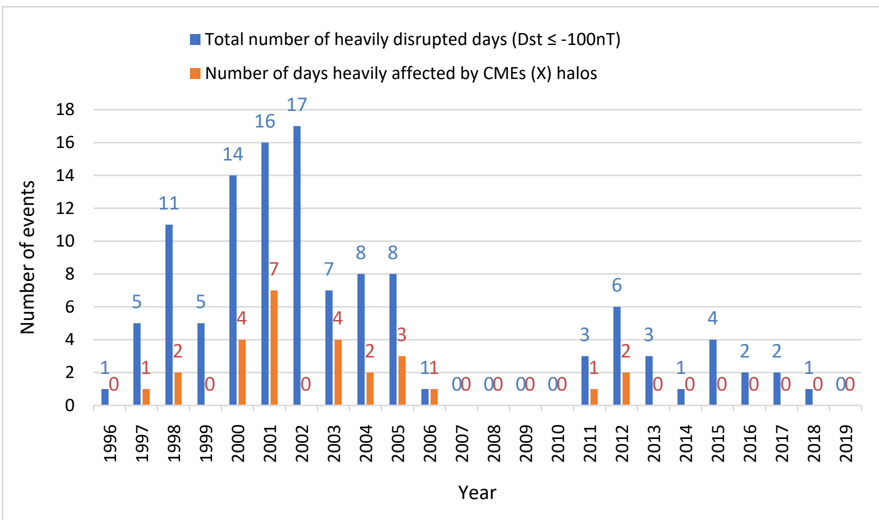

Figure 3. Distribution of days with severe disturbances and severe disturbances days caused by coronal mass ejections halos (X) during the periods 1996-2019.

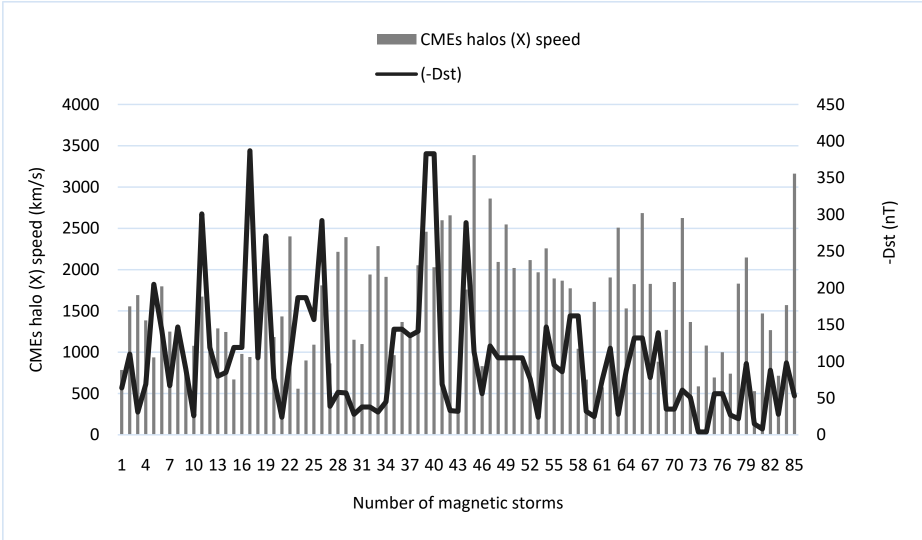

Figure 4. Speed profiles of the 85 halo coronal mass ejections associated with X-class eruptions (histogram) and the associated magnetic disturbances.

Table 2. Number of halo coronal mass éjections associated with X-class flares and number and percentage of intense geomagnetic storm (Dst ≤ −100 nT) produced during solar cycles 23 and 24.

	CME halos associated with X-class flares	Intense geomagnetic storms (Dst ≤ −100 nT)
Solar cycle 23	59	32 (≈54%)
Solar cycle 24	27	4 (≈15%)
Total	86	36 (≈42%)

To summurise, about 42% of halo CMEs (X) with velocities in excess of 1000 km/s caused intense geomagnetic disturbances.

Furthermore, 21 out of 85 halo (X) CMEs have a speed of less than 1000 km/s and 9 out of 21 are associated with a Dst value of less than −100 nT, showing that about 43% of halo (X) CMEs with speed below 1000 km/s have also caused intense geomagnetic disturbances.

Table 3 provides summary statistics, such as mean, variance, standard deviation and median for CME speed.

Table 4 provides summary statistics, such as mean, variance, standard deviation and median for Disturbance storm time values.

4. Discussion

Although ordinary coronal mass ejections can be observed at all phases of a solar cycle, they represent a population of CMEs that have no impact on Earth. This is not the case for halos coronal mass ejections (directed towards the Earth), in particular those associated with class-X flares (halos CMEs (X)). halos CMEs (X) classified as intense solar events because of their impact on the Earth's magnetic field and their effects on current technologycal systems are very rare. They can

Table 3. Mean, variance, standard deviation and median for coronal mass ejections speed.

CMEs speed (km/s)				
	Mean	Variance	Standard deviation	Median
Two cycles	1555.09412	451854.462	672.201	1469
Cycle23	1590.65517	424124.64	651.2485	1494.5
Cycle24	1478.7037	502870.209	709.133	1469

Table 4. Mean, variance, standard deviation and median for Disturbance storm time values.

Dst (nT)				
	Mean	Variance	Standard deviation	Median
Cycle 23	−124.448276	8164.07491	90.3552	−105
Cycle24	−58.7037	1624.5048	40.3051	−53

also be observed at all phases of a solar cycle. However, they are even rarer or non-existent during the minima of solar cycles. Their occurrence can reach a remarkable peak during the ascending, maximum or descending phases. These observations show that the Sun can have intense activity at any phase of its cycle. The idea of predicting an intense solar event therefore becomes difficult to support.

An intense event can be considered as an event that presents unique characteristics in its origin (characteristics linked to the size of the flares, the kinetic energy or the speed of the CMEs) or in its consequences (intense geomagnetic storms, solar proton events intense) [4].

There are two types of closed field region known to produce CMEs: sunspot regions (active regions) and quiescent filament regions [5]. The fastest CMEs come from active regions because they have the magnetic energy needed to supply them [6]. All the halo CMEs associated with X-class flares therefore come from active regions with speeds exceeding 1000 km/s on average.

However, the speed of these CMEs is no indication of their ability to affect the geomagnetic field and generate intense storms. Our statistical study of 85 halos CMEs (X) showed that about 43% of halos CMEs (X) travelling at less than 1000 km/s can also produce intense storms. The reason why some very energetic halos CMEs (X) are not geoeffective could be partly due to a loss of magnetic energy during the Sun-Earth journey. CMEs can only be powered by the magnetic energy in the Sun's closed magnetic field regions [7].

Note that high-speed compressible flows can undergo very rapid variations in their characteristics over very short distances. The particles in these flows undergo a sudden, discontinuous change in speed, known as a shock. There is a sudden discontinuity in speed, pressure, temperature and density. This is accompanied by a decrease in energy and an increase in entropy.

Like high-speed compressible flows, fast CMEs are subject to changes as they move along. This result is consistent with the work of [8].

Table 2 shows that the number of intense geomagnetic storms (Dst ≤ −100 nT) caused by CMEs associated with X-class flares is higher during solar cycle 23. This observation agrees with several studies such as those by [9]. By comparing the ascending phases of the two solar cycles, they showed that there were 10 intense storms and no violent storms during the first 4 years of cycle 24, compared with 21 intense storms and 4 violent storms during the same period in cycle 23. Cycle 23 was very agitated by intense coronal mass ejections with speeds in excess of 1000 km/s. Most of these high-energy storms caused large magnetic perturbations.

Some very energetic CMEs were not geoeffective: the CME of 4 November 2003, which had a speed of 2657 km/s and was classified as an extreme storm (class X28), was associated with a Dst of −33 nT [10]. Also, some intense geomagnetic storms were not associated with any halo (X) coronal mass ejections, such as the geomagnetic storm of 22 October 1999 with a minimum Dst of −237 nT.

In Table 3, the CME (X) of solar cycle 23 have on average higher velocities than the CME (X) of solar cycle 24. This proves that the events during solar cycle 23 were very energetic. The standard deviation of the solar cycle 24 for CME(X) velocities is higher. The CME(X) velocities of solar cycle 24 are much more dispersed than those of solar cycle 23. This means that more varied velocity values were recorded during solar cycle 24 than during solar cycle 23.

As an interpretation, we counted 20 distinct active regions during solar cycle 24. These active regions produced 27 CMEs (X). 05 of the 20 active regions are recurrent active regions (from which several CMEs originate). Observations confirm that speeds are high in these recurrent regions and vary much more than speeds in regions which are not recurrent. The number of these recurrent regions is thought to influence the fluctuation in velocities observed during the solar cycle 24. It appears that the larger the recurrent active regions in a solar cycle, the more the CME speeds fluctuate. Recurrent active regions have very high magnetic energy, which explains their ability to produce multiple coronal mass ejections. They are considered to be an essential parameter for space weather forecasting.

In Table 4, the mean and median Dst data for solar cycle 23 are higher in absolute value than those for solar cycle 24. The geomagnetic field during solar cycle 24 therefore appears to be less disturbed by CMEs (X) than during solar cycle 23. The standard deviation of Dst values for solar cycle 23 is also higher than for solar cycle 24. The Dst values recorded during solar cycle 23 are more dispersed than those recorded during solar cycle 24. The Earth's magnetic field during solar cycle 24 was more stable than during solar cycle 23.

The low geomagnetic activity observed during solar cycle 24 is not due to a low rate of solar storms. In fact, during the years 2012, 2013 and 2014, we observed 20 CMEs (X) and 10 intense geomagnetic storms, of which 02 were caused by halo CMEs (X).

These results demonstrate the absence of events in the presence of an interplanetary magnetic field strong enough to generate intense geomagnetic disturbances. They are in agreement with those of [11].

We also found that the high class of the flare does not always play a key role in determining the strength of a storm (29% of CMEs associated with X-class flares are non-geoeffective). This finding corroborates the work of [3].

[12] has shown that negative values of the Bz component ($Bz \leq -20$ nT) of the interplanetary magnetic field imply a north-south orientation of this component, *i.e.* in the opposite direction to the south-north (geographical) orientation of the Earth's geomagnetic field.

This configuration favours magnetic reconnection between the Earth's magnetic field and the Bz component of the interplanetary magnetic field, allowing solar wind particles to penetrate strongly into the magnetosphere.

Intense geomagnetic disturbances would then be conditioned by the north-south orientation of the Bz component of the interplanetary magnetic field.

The initial speed of a fast halo CME (X) can be the cause of an intense geomagnetic storm provided that the (Bz) component of the interplanetary magnetic field is directed southwards.

5. Conclusions

Our statistical study shows that:

- Solar Cycle 23 was a magnetically strong solar cycle: numerous halo coronal mass ejections associated with X-class flares were observed and 54% of these CMEs triggered intense magnetic storms.

- Solar Cycle 24 was a short and magnetically weak cycle: fewer halo coronal mass ejections associated with X-class flares were observed, and 15% of these CMEs caused intense magnetic storms.

Fast halo (X) CMEs are likely to be geoeffective. In addition to the initial speed, the southern orientation of the Bz component of the interplanetary magnetic field would be necessary for this geoeffectiveness. Some slow halo (X) CMEs have also been found to be geoeffective.

The Sun can be intensely active at any phase of its cycle. This is a major concern when it comes to predicting intense solar events.

The statistical study of coronal mass ejections associated with X-class flares has highlighted a key parameter for understanding the speed distribution of these events, and the way in which these CMEs can affect the Earth's magnetic field: recurrent active regions. Using statistical data, we calculated the mean, median and standard deviation of the two variables (Speed, Dst) and established that the high dispersion of CME (X) speed and the low geomagnetic activity during solar cycle 24 are linked to the source of these CME (X), *i.e.* active regions which are not recurrent. A disturbed solar cycle would have more recurrent active regions.

Since the study focused on a sample of Halo (X) CMEs in order to understand their dynamics, these results contribute to our understanding of solar activity. This study highlights the need to continue monitoring the Sun, particularly active regions, in order to refine our knowledge of Sun-Earth interactions.

When a CME arrives on Earth, it can cause an intense geomagnetic storm as well as intense auroral activity, and can cause damage to a wide range of activities and equipment, including radio communications, GPS, radar systems, satellites, electronic devices, and so on.

Our study is limited by the fact that measurement errors are not taken into account and that there may be gaps in our data. These aspects could be better dealt with in a more in-depth study of the variability of speed depending on the source of the CMEs.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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