MAGNETIC BUILD-UP AND PRECURSORS OF CMES

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ABSTRACT

CMEs are fundamentally magnetic phenomena, thus to improve CME forecast we have to find out more about the characteristics of the small and large-scale magnetic field in and around their source region prior to CME occurrence. In this paper we show examples of the magnetic evolution of CME-poor active regions using SOHO/MDI data. It appears that CMEs are preceded by magnetic evolution during which the helicity of the source region is increasing due to twisted flux emergence, shearing motions between opposite polarity footpoints of subsequently emerging bipolar and, in a smaller extend, by the differential rotation acting on the emerged flux. Furthermore, we find short-term magnetic precursors of CME events, typically a combination of major flux emergence, cancellation and fast shearing motions in active regions with strong concentrated magnetic fields prior to flare-related CMEs and small-scale cancellation events along the magnetic inversion line in decayed active regions with low magnetic flux density prior to filament eruption-related CMEs. We make an overview of recent studies on magnetic helicity and suggest that such analyses will be able to provide a key to unlock the secrets of CME buildup and initiation.

Key words: solar magnetic field, CME, flare, precursor.

1. INTRODUCTION

Magnetism is the key to understanding the Sun. Monitoring small- and large-scale solar magnetic fields is absolutely necessary for making better predictions of space weather phenomena.

CMEs, which play a crucial role in space weather, draw their energy from the available free magnetic energy and are related to large-scale re-organization of the solar magnetic fields. Thus they are fundamentally magnetic phenomena. During the last two solar cycles important progress has been made in understanding the build-up and initiation of flares, resulting in an improved flare forecast ability. Now the time has come to make a similar effort and progress in understanding the build-up and initiation process of CMEs.

In this paper, after a short overview of the main rules/laws governing magnetic surface patterns, we summarize some principal magnetic properties in ARs which are known to precede flare activity. Then we define some basic similarities and differences between flares and CMEs and show examples of magnetic evolution of CME-poor active regions and magnetic precursors of CMEs. The clues we find are consistent with the idea that magnetic helicity plays a crucial role in the CME initiation process, and the lack or presence of near-threshold helicity in the AR during periods when conditions in it match flaring conditions may be a key difference between conditions leading to confined flares or eruptive CMEs.

2. MAGNETIC PATTERNS OF SOLAR ACTIVITY

The best known magnetic pattern in solar activity is the Hale-Nicolson polarity law (Hale & Nicholson, 1925), which describes that the magnetic polarity of sunspot groups (i.e. the polarity of the spot, which "leads" in the sense of solar rotation) are the opposite on the northern and the southern hemispheres. The first spot groups of the 11-year cycle appear at high latitudes and as the cycle progresses the mean latitude of spots on both hemispheres steadily decreases, while their polarity remains unchanged. However, the polarity of spot groups change cycle to cycle, thus a full magnetic cycle lasts for 22 years.

A more recently recognised rule concerns the hemispheric pattern of the helicity in solar activity phenomena (Seehafer, 1990; Pevtsov, Canfield & Metcalf, 1995). Magnetic helicity is a measure of the linkage of the magnetic field lines within a volume. It can be expressed as the sum of twist and the writhe of a magnetic configuration.

Magnetic helicity can be computed as $H = \int_{V} \vec{A} \cdot \vec{B} dV,$
where \( \vec{A} \) is the magnetic vector potential, \( \vec{B} = \vec{\nabla} \times \vec{A} \) is the magnetic induction. For a force-free magnetic field \( \vec{\nabla} \times \vec{B} = \alpha \vec{B} \), where \( \alpha \) is the force-free parameter. In the linear force-free approximation \( H_{am} \propto \alpha \). Thus, the sign of \( \alpha \) defines the sign of helicity. In the majority (70-80 %) of solar active regions, \( \alpha \) was found positive on the southern and negative on the northern hemisphere (Pevtsov, Canfield & Metcalf, 1995). This hemispheric helicity rule is invariant, i.e. it does not change from cycle to cycle, unlike the polarities of the spot groups. Other solar activity features, which represent different aspects of the helicity and were named by different authors using different conventions, follow the rule and are summarised in Table 1.

3. CONDITIONS FOR IMPORTANT FLARE ACTIVITY

The appearance of an active region classified as \( \delta \) (umbrae of opposite polarities separated by less than 2 heliographic degrees within the same penumbra; Künzel, 1960), or \( \gamma - \delta \) (a complex active region in which the positive and negative polarities are irregularly distributed containing one or more delta spots), especially with high magnetic flux content (\( \geq 3 \times 10^{23} \) Mx) increase very much the probabilities for the occurrence of M and even X-class flares (Zirin & Liggett, 1987; Zirin, Marquette, 1981; Semmes, Tang, & Zirin, 2000). Furthermore, observations of magnetic fields associated with solar flares show that flares are likely to occur close to sunspots in regions where the magnetic field is sheared along the polarity inversion line and (1) the maximum shear angle exceeds 85 degrees; and (2) the extent of strong shear (shear angle greater than 80 degrees) exceeds 10,000 km (Moore, Hagyard, & Davis, 1987; Hagyard, Venkatakiran, & Smith, 1990; for models see also: Antiochos, 1998; Antiochos, DeVore & Klimchuk 1999).

Confined flares relieve local magnetic stresses, i.e. free accumulated energy from, on the solar scale, relatively small volume. Such flares re-distribute, but conserve helicity. On the other hand, eruptive flares liberate stored magnetic energy over a larger volume. They lead to the partial opening of the field and helicity does not remain conserved in a volume on the active region scale.

For the occurrence of eruptive flares the presence of a sheared arcade or a twisted flux tube (frequently occupied or manifested by a filament), where the shear or twist are increasing, seem to be necessary conditions. The scenarios proposed can be roughly divided into two categories, of which we show two recent examples below.

An eruptive flare scenario, developed for the 14 July 1999 flare, was described by Aulanier et al (2000). These authors showed that shearing motions in a delta-spot led to a field line expansion which caused first a slow, then a fast reconnection in the vicinity of the 3-D null-point present above the AR, and led to partial field line opening. Besides the increasing shear, the complex magnetic topology and the presence of the null-point were necessary conditions in the eruptive flare process, as predicted in the "break-out model" by Antiochos et al. (1999).

Another scenario, which concerns a twisted flux tube, according to Titov and Démoulin (1999) and Fang et al. (2000) is the following: the flux rope (or filament) loses its equilibrium and moves upward. A current sheet is formed below the filament. If there is no reconnection or the reconnection is not fast, the filament will finally stop rising and fall down, while when fast reconnection occurs, the filament erupts. After the reconnection, cusp shaped hot X-ray loops are formed, a well-known signature of eruptive solar flares (Fig. 1).

4. ARE THE CONDITIONS FOR FLARE AND CME ACTIVITY DIFFERENT?

The cusp shaped X-ray loops (arcades) which characterise eruptive flares are also used as proxy for CMEs (Sterling et al, 2000), since such eruptive flares inevitably become CMEs. Thus, conditions for CME activity in the early stage of active region evolution are similar to those of eruptive flares.

About 93 % of the flare activity (only part of them are eruptive!) arises in active regions which contain sunspots (Dodson & Hedeman, 1970), while the span of CME activity is much longer and well extends into the phase of active region evolution when the magnetic field is dispersed and the region is frequently classified as quiet solar region, which contains a filament (van Driel-Gesztelyi et al, 1999). The two classes of CMEs, namely the flare-related CME events and the CMEs associated with filament (or, on the limb, prominence) eruption are well reflected in the evolution described above: in a young active region with major sunspots mainly flare-related CMEs appear, and as the magnetic flux of the active region is getting dispersed, the non-flare, filament-eruption related CMEs will become dominant. However, since filaments are present even in active regions which still contain strong magnetic field concentrations (spots), and flare events in such regions are associated with the eruption of the filament, mixed cases are not rare. A high level of magnetic non-potentiality, which is normally associated with flaring young active regions, may persist or can even grow after the strong magnetic concentrations (sunspots) disappear (van Driel-Gesztelyi et al, 1999; Démoulin et al, 2001b). Thus, it is important to follow solar active regions throughout their evolution well into their decay phase and monitor their level of magnetic non-potentiality and CME activity, in order to understand the underlying physics and to enable us to forecast CMEs like the strongly geoeffective 6 January 1997 halo CME, which came from a dispersed magnetic region and had only very weak lower coronal signatures.

In the ‘eruptive flare + filament eruption → CME’ scenario described above (Titov and Démoulin, 1999; Fang et al, 2000) the first step is that a flux rope loses equilibrium and starts rising. However, questions remain why the flux rope is present and why such loss of equilibrium occurs leading to a CME.
Table 1. Dominant hemispheric helicity conventions for different solar features

<table>
<thead>
<tr>
<th>Features</th>
<th>Northern hemisphere</th>
<th>Southern hemisphere</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>sunspot whirls(*)</td>
<td>counter-clockwise</td>
<td>clockwise</td>
<td>(1,2)</td>
</tr>
<tr>
<td>helicity sign in ARs</td>
<td>negative</td>
<td>positive</td>
<td>(3,4)</td>
</tr>
<tr>
<td>sigmoidal coronal structures</td>
<td>backward-S</td>
<td>forward-S</td>
<td>(4,5,6)</td>
</tr>
<tr>
<td>filaments</td>
<td>dextral</td>
<td>sinistral</td>
<td>(7,9)</td>
</tr>
<tr>
<td>coronal arcades</td>
<td>left-handed</td>
<td>right-handed</td>
<td>(8,9)</td>
</tr>
</tbody>
</table>

(*) spiral pattern of the penumbral fibrils

(1) Hale & Nicholson (1925)
(2) Richardson (1941)
(3) Seehafer (1990)
(4) Pevtsov, Canfield, Metcalf (1995)
(5) Rust and Kumar (1996)
(6) Canfield, Hudson & McKenzie (1999)
(7) Martin, Bilimoria & Tracadas (1994)
(8) Martin & McAllister (1997)
(8) Martin (1998)

Figure 1. Sigmoid formation by reconnection of two J-shaped loops and cusp formation after the sigmoid ejection. (a) Pre-reconnection configuration. Such two J-shaped loops are frequently observed in soft X-rays. (b) Reconnection forms a long sigmoid and short, bright loops around its middle part. (c) The sigmoid expands, building a current sheet below it, which creates a cusp above the short reconnected loops. In both (a) and (b) two characteristic field lines, not involved in the reconnection, have been added as a guide for the full magnetic configuration. They are representative of the large-scale arcade and of the twisted flux tube. "I.L." indicates the magnetic inversion line (from van Driel-Gesztelyi et al, 2000). A typical sigmoid expansion was shown by Manoharan et al. (1996).

A twisted flux tube can be formed in the corona either by magnetic reconnection in a sheared arcade or by emergence from the corona's convective zone (for a discussion see van Driel-Gesztelyi et al, 2000). Both processes can progressively bring the magnetic configuration to an unstable state. Such eruption of a twisted flux-tube has been proposed by several authors (e.g. Martens and Kuin 1989; Moore and Roumeliotis 1992; Forbes 1992; Lin et al. 1998; Titov and Démoulin 1999). Figure 1. shows the main characteristics predicted in such models: (i) a sheared arcade and a twisted flux tube embedded in it, (ii) reconnection forms long sigmoidal loop and short loops in the middle of the arcade, (iii) the sigmoid expands, due to a re-distribution of twist during reconnection and a consequent instability, building a current sheet below it, which creates a cusp above the short reconnected loops. Note that an unstable state is probably reached by increasing shear and/or twist.

5. FLARE-RELATED CME EVENTS IN ACTIVE REGIONS

The south hemispheric AR 8100 produced at least nine flare/CME events during its disc passage in November 1997 (Delannée et al, 2000).

The magnetic topology of NOAA 8100 became complex due to repeated flux emergence at its NW edge (Fig. 2). One of these new bipole was the primary centre of eight of the nine eruptive events (CMEs), which originating from this region. The magnetic stresses were not high in the AR as a whole (Yan & Sakurai, 2000), but local stresses were created between the fast-moving trailing parts of the new bipole and the leading spots of the main bipole, since they moved in opposite directions.
There was a significant flux imbalance in the AR due to flux emergence in its trailing part. Flux imbalance forces the AR to develop external magnetic connections. Indeed, large-scale loop connections between the North hemispheric AR 8102 and AR 8100 were seen. The eruption of these large-scale loops made the CMEs truly large-scale (Kahn & Hudson, 2000; Maia et al, 1999).

Delannée, & Aulanier (2000) analysed the flare which occurred on 3 November 1997 at 10:31 UT in the vicinity of the new flux emergence in the NW part of the AR, the positive polarity part of which they refer to as parasitic polarity. Using SOHO/EIT 195 Å observations, they identify the brightening of thin trans-equatorial loops connecting AR 8100 and AR 8102, and dimmings located between the two active regions. Difference images highlight the presence of a loop-like structure rooted near the flare location. The coronal magnetic field derived from potential extrapolations from a SOHO/MDI magnetogram showed that the topology was complex near the parasitic polarity and a so-called ‘bald patch’ was present (where the magnetic field is tangent to the photosphere), which is a flare-active magnetic topology (Titov et al, 1993; Aulanier et al 1998). Delannée, & Aulanier (2000) propose that the large-scale trans-equatorial field lines were pushed up by the opening of low-lying sheared field lines forming the bald patch. In this scenario the large-scale magnetic topology combined with magnetic evolution in the principal CME source region both are crucial conditions in the CME initiation. A similar scenario can be applied to the 6 Nov. 1997 event (Maia et al, 1999 and the 2 May 1998 event (Pohjalainen et al, 2001), which both involved the eruption of trans-equatorial loops.

6. FILAMENT-ERUPTION RELATED EVENTS IN REGIONS WITH DISPERSED MAGNETIC FIELD

The source region of the 6 January 1997 halo CME had dispersed magnetic fields; it was the remnant of NOAA 8003, which was the first major cycle 23 AR on the South hemisphere. Its emergence in December 1996 was
well observed with the SOHO/MDI magnetograph. The sunspot group was built up by at least two medium-sized bipoles which emerged with a time difference of 2 days. The second bipole appeared next to the fast-moving leading (negative) spots of the first bipole.

The magnetic field was still relatively strong during the 2nd rotation of this AR (January 1997), and by then the shearing effect of the differential rotation was well seen. There was a filament along the magnetic inversion line stretching southward from the center of the AR, which joined to the E-W polar crown filament forming a "switchback", an inversion line with a sharp change of direction. This switchback ran from NSE-WE (backward L) direction, thus it was a typical "rising phase of the cycle" type.

The CME source region (AR 8003) had positive helicity corresponding to the hemispheric helicity rule, as manifested by the "forward S" sigmoidal coronal loops in the Yohkoh/SXT images. In the centre of the AR approaching motion and cancellation of opposite polarity magnetic fields was observed starting on 4-5 January (Fig. 3).

A small CME occurred on 5 January between 1331-1610 UT, followed by a second (highly geoeffective) CME (Fox et al., 1998). The latter was related to the expansion of coronal sigmoids on 6 January between 1338-1423 UT (Fig. 4). Webb et al. (1998) described plage fluctuations in the centre of the AR (S35,E05) and the appearance of two small sunspots, implying flux emergence prior to the 6 January CME. However, neither in the MDI magnetic field nor in the white-light movie we made could we find any sign of new flux emergence or spot appearance (it is a "spotless" AR). However, the magnetic field subjected to supergranular motions may concentrate at places where several supergranules meet and this might give the impression of new flux emergence. We suggest that the dominant magnetic event prior to the CME was flux cancellation rather than flux emergence.

The 6 January instability included the DB of a filament segment (S23,W03) which was about 15° long and disappeared between 1301-1453 UT (Webb et al., 1998). This filament was newly formed before its DB, because it was not visible in the Meudon Hα image taken at 0850 on 6 January. A filament was activated also South to the AR. The CME was related to a large-scale instability. However, its likely cause was the eruption of the twisted flux tube of the filament along the magnetic inversion line of the AR, and it was initiated in the centre of the AR where the observed flux cancellations took place.

During the 3rd return of NOAA 8003 onto the visible hemisphere, there were again geoeffective CMEs, which originated from this AR; the 6-7 February CMEs. The principle cause of the instability seems to be the same as for the 6 January event: accumulated helicity by the differential rotation and small-scale cancellations along the magnetic inversion line, which we clearly saw in the MDI magnetic field movies.

Another similar case: opposite polarity magnetic field concentrations moved towards the magnetic inversion line under a filament and augmented the shear before the 25/26 Sept. 1996 halo CME event (Schmieder et al., 2001).

7. DISCUSSION ON THE ROLE OF MAGNETIC EVOLUTION OF THE SOURCE REGION IN THE INITIATION OF CMEs

Aulanier et al. (2000), analysing the 14 July 1999 (Bastille-day) flare, which occurred in a delta-spot group, showed that shearing motions in the delta-spot led to a field line expansion which caused first a slow, then a fast reconnection in the vicinity of the 3-D null-point present above the AR. The resulting eruptive flare and CME, therefore, was preceded by important sunspot motions. More precisely, it was the magnetic evolution, indicated by the sunspot motions, which was one of the causes of the eruption. However, the complex magnetic topology and the presence of the null-point were other necessary conditions in the flare/CME process. In other active regions, like NOAA 8100 in November 1997 and NOAA 8210 in May 1998 which produced several CMEs during their disk passage (at least nine [DeLanée et al., 2000] and five, respectively), both ARs showed important magnetic evolution involving flux emergence and cancellation, and again, shearing motions between opposite polarity spots belonging to pre-existing and emerging bipoles. The commencement of CME activity in these regions coincided with the appearance of new flux and ensuing shearing motions. Though the magnetic field topology can be quite different, a scenario similar to the 1999 "Bastille-day flare" could be applicable to other active regions.

However, the presence of sunspots and sunspot motions is not a necessary condition for flare and especially not for CME occurrence. As active regions decay, their flux is getting more and more dispersed and spots disappear. Along the lengthening inversion line, which is more and more bent by the differential rotation, long filaments form and their eruption is also related to CME events. In magnetic movies using MDI magnetograms with a 96-min cadence we found small-scale magnetic changes preceding the initiation of the CME, most of the cases magnetic cancellation started a few hours or days before the CME in the centre of the AR, along the magnetic inversion line under the filament, e.g. in the remnant of NOAA 8003, where the geoeffective CME of 6 January 1997 originated from. However, we would like to emphasis that such small-scale magnetic changes represent just the "last drop in the glass" in destabilising a magnetic system which is already close to its stability threshold. Although helicity is conserved, it is re-distributed during magnetic reconnection, cascading towards the larger scale. Thus, the reconnection associated to the cancellation events can lead to an increase of magnetic stresses (twist/helicity) of the twisted flux tube of the filament along the magnetic inversion line. When the magnetic stresses along the filament are close to threshold, such small helicity input can lead to the destabilization of the filament. Thus, the flux cancellations can not be regarded as the direct cause of the eruption but they were simply part of a long-term process which increased the helicity in the AR. Helicity is slowly accumulated by the differential
Figure 3. Magnetic evolution of the source region of the 6 January 1997 CME. From Note the approaching motion and cancellation of the opposite polarity magnetic concentrations prior to the CME event, which started on 6 January between 1338-1423 UT. SOHO/MDI full-disc observations. The images have been rotated to an epoch close to the central meridian passage of the AR in order to remove geometric projection effects.

Figure 4. Yohkoh/SXT images show sigmoidal coronal loops before the CME events, on January 5, at 13:21 and on January 6 at 11:59 UT.

rotation (DeVore, 2000), replenished from the subphotospheric twist of the flux tube via torsional Alfvén waves (Longcope & Welsch, 2000; Démoulin et al, 2001b) and occasional helicity injection from small-scale flux emergence and helicity-redistribution from flux cancelling at the inversion line.

The above picture may be more complicated when an AR has large-scale, or even trans-equatorial loop connections, an eruptive flare in the AR may make the large-scale loops erupt as well. Most of the CMEs which involved eruptive flares in NOAA 8100 (in Nov. 1997) and also in NOAA 8210 (in May 1998) became large-scale events due to the eruption of their trans-equatorial loop connections (Delanné and Aulanier, 1999; Pohjalainen et al, 2001; Khan and Hudson, 2000). As Canfield, Pevtsov, McClymont (1996) and Pevtsov (2000) found that there is a tendency for ARs which have the same handedness (helicity sign) to form trans-equatorial loops. This implies that one of the ARs should disobey the hemispheric helicity rule (Table 1). NOAA 8100 was a south
hemispheric region, which had negative helicity (Green et al., 2001a,b) opposite to the majority of ARs on that hemisphere. It was connected to the vicinity of the northern hemispheric NOAA 8102, where a "backward-S" shaped sigmoid (negative helicity) was seen in YOHKOH/SXT images for several days. Thus, these two active regions had the same helicity indeed.

The Sun has to get rid of the continuously amounting helicity, created by the solar dynamo (e.g. Seehafer, 1990) and brought up by the emergence of twisted flux (Leka et al., 1996; Longcope & Welsch, 2000; Démo\l\, et al., 2001b), furthermore, increased by differential rotation (DeVore, 2000, Démo\l\, et al., 2001a,b, Green et al., 2001a,b), and localised shearing footpoint motions (Démo\l\, et al., 2001a). CMEs are prime candidates for performing that task (Rust, 1994, Low, 1996).

8. CONCLUSIONS

Conditions for CMEs:
- eruptive flare occurrence: complex magnetic topology, presence of a magnetic null low in the corona, presence of large-scale magnetic stresses, high level of helicity, magnetic evolution increasing shear or twist;
- filament eruption: high level of helicity, magnetic evolution in the form of
  (a) small-scale flux emergence or flux cancellation along the magnetic inversion line, i.e. under the filament
  (b) flux emergence or, in general, magnetic field evolution in the vicinity of the filament.

Conditions for large-scale CME events extending to both hemispheres:
- having the same sign of helicity increases the probability of inter-AR connectivities, which can be destabilised by eruptive events at either footpoint; in case of trans-equatorial connectivities this implies that one of the ARs disobeys the hemispheric helicity rule; such peculiar regions may be highly CME productive.

The main similarities between confined flares and CMEs:
- they both are preceded by instabilities of the magnetic configuration;
- their process involve magnetic reconnection;
- they liberate free magnetic energy.

The main differences between confined flares and CMEs:
- confined flares release localised magnetic energy and do not create open field line configurations, do not change the helicity (though may redistribute it), and they are initiated when local magnetic stresses reach threshold.
- CMEs are large-scale instabilities, release free magnetic energy from an extended volume and carry away magnetic helicity, relieving the Sun from the continuously amounting helicity; CMEs may be initiated by helicity reaching threshold.

As the examples presented above indicated, CMEs are preceded by a long-term build-up process, along which flux emergence, shearing and twisting footpoint motions are seen. The short-term precursors of CMEs may be as unimpressive as just small-scale flux emergence and cancellation events. However, all these processes are actually increasing magnetic helicity in the AR, except for the cancellation events, which redistribute helicity, cascading towards the longer scale.

However, the above mechanisms have very different efficiency in injecting helicity into the corona. Démo\l\, et al. (2001a, 2001b) and Green et al. (2001a,b) showed that the differential rotation is a very inefficient generator of helicity, as a result of a partial cancellation of twist and writhe helicities, which have opposite signs. On the other hand, shearing motions localised between two polarities are more efficient and lead to a monotonous increase of coronal helicity since in such localised case twist and writhe helicities have the same sign and add up (Démo\l\, et al., 2001a). However, since they involve only a fraction of the AR flux, the helicity generated by such shearing motions is, in most cases, relatively small compared to the helicity needed for a CME (cf. Chae, 2001; Chae et al., 2001; Démo\l\, et al., 2001b, Green et al., 2001b). Analysing the long-term helicity budget of two CME prolific active regions (AR 7978 and AR 8100) Démo\l\, et al. (2001b) and Green et al. (2001a,b) concluded that the main source of coronal magnetic helicity must be the inherent twist of the emerging flux tubes. Furthermore, during the decay phase of ARs the subphotospheric twist can be transferred into the corona by a very slow continuous hardly observable emergence of the flux tube or more probably by torsional Alf\é\n\é\n waves (Longcope & Welsch, 2000), replenishing the helicity after relaxation i.e. CME events. The above arguments imply that the CME activity is at a source region mainly depends on the amount of twist its flux tube brings up from the bottom of the connection zone. However, the magnetic complexity in the AR and whether it conforms or not to the rules found in the large-scale magnetic patterns may also have strong effect on its CME productivity.

This work provides one of the starting points of an ambitious project on CME initiation, propagation and interaction in which we combine multiwavelength observations with modelisation and MHD simulations of such events following them from the Sun to the Earth (see also Poedts et al., 2001).

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