The Astrophysical Journal, 626:574–578, 2005 June 10

THE MAGNETIC STRUCTURE OF FILAMENT BARBS

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Received 2005 January 12; accepted 2005 February 16

ABSTRACT

There is a controversy about how features protruding laterally from filaments, called barbs, are magnetically structured. On 2004 August 3, we observed a filament that had well-developed barbs. The observations were performed using the 10 inch refractor of the Big Bear Solar Observatory. A fast camera was employed to capture images at five different wavelengths of the Hα line and successively record them on the basis of frame selection. The terminating points of the barbs were clearly discernable in the Hα images without any ambiguity. The comparison of the Hα images with the magnetograms taken by *SOHO* MDI revealed that the termination occurred above the minor polarity inversion line dividing the magnetic elements of the major polarity and those of the minor polarity. There is also evidence that the flux cancellation proceeded on the polarity inversion line. Our results together with similar other recent observations support the idea that filament barbs are cool matter suspended in local dips of magnetic field lines, formed by magnetic reconnection in the chromosphere.

Subject headings: Sun: filaments — Sun: magnetic fields — Sun: prominences

1. INTRODUCTION

For a long time it has been believed that the cool matter of filaments is supported in diplike horizontal magnetic structures (see Tandberg-Hanssen 1995 for review). Using the idea of magnetic dips, Aulanier and his colleagues (Aulanier & Démoulin 1998; Aulanier et al. 1998, 1999) modeled realistic three-dimensional magnetic configurations that successfully produced the morphology of filaments. An important characteristic of their models is that they can naturally explain not only the morphology of the main body (called the spine) of a filament, but also that of features (called barbs) protruding laterally from the spine. According to the models, barbs represent cool matter residing in small dips formed above the secondary photospheric inversion lines around parasitic magnetic elements whose polarity is opposite to the dominant polarity of surrounding magnetic elements and hence is called minor polarity.

The traditional idea of magnetic dips in filaments, however, was recently challenged by two kinds of new observational findings. One is the existence of closely spaced flows of opposite directions along individual threads comprising filaments, which are called counterstreaming flows (Zirker et al. 1998; Lin et al. 2003). This kind of flow in filaments was already reported in the earlier Doppler shift observation performed by Schmieder et al. (1991). Zirker et al. (1998) found that the counterstreaming flows extend from the spine down to the chromosphere, or vice versa, through barbs. Supposing that the flows are field-aligned, they proposed that field lines in the barbs are predominantly vertical and directly connect the filament to the photosphere. After the report of the counterstreaming flows, the occurrence of higher speed flows in filaments (mostly along the spines, not in barbs) was often reported from observations at the Hα line (Chae et al. 2000; Jing et al. 2003), at the He II λ304 line (Wang 1999), and at other UV/EUV wavelengths (Kucera et al. 2003; Chae 2003). The high-speed flows observed by Kucera et al. (2003) were more typical of activated filaments than quiet ones, and those observed by Chae (2003) were associated with canceling magnetic features and were thought to be relevant to the formation of a filament. The various observed flows suggest that filaments may be much more dynamic than previously thought.

In this line of thought, Karpen et al. (2001, 2003) proposed that magnetic dips are *not* necessary for the formation and maintenance of a filament if it can be regarded as a dynamic entity. Using numerical experiments, they showed that thermal nonequilibrium in long arched loops without any dip yields dynamically evolving condensations that appear to be consistent with observed filament characteristics. Litvinenko (2000), on the other hand, regarded the observed small speeds of flows in barbs as evidence for the almost magnetohydrostatic nature of the barbs and showed that the flows can be modeled by perturbing the magnetohydrostatic solution. According to this explanation, the flows in a barb are not field-aligned, nor is the predominant direction of magnetic field lines along it, and hence, the existence of flows does not counter the idea that barbs represent cool matter suspended in low-lying magnetic dips as modeled by Aulanier et al. (1998).

Another kind of observational finding put forward as evidence against the diplike magnetic configuration of barbs is that barbs are rooted in parasitic magnetic elements of minor polarity (Martin & Echols 1994; Martin 1998). This finding is similar to the models of Aulanier et al. (1998) in that barbs are associated with minor polarities. But the wire model proposed by Martin & Echols (1994) employs no magnetic dips, whereas an important consequence of the models of Aulanier et al. (1998) is the natural presence of dips. This noteable difference is directly related to the critical question whether the ends of barbs are located just above the minor polarities (Martin & Echols 1994; Martin 1998) or above minor polarity inversion lines adjacent to these (Aulanier et al. 1998). In this strict sense, we note that the finding of Martin & Echols (1994) has not been supported by other subsequent investigators. The only other reference cited by Martin (1998) is Engvold & Yi's unpublished work, the results of which were briefly mentioned by Engvold (1998), but which may not necessarily support those of Martin (1998).

Wang (2001) examined the relationship between the barbs of He II λ304 filaments and the photospheric magnetic field and found that the ends of barbs overlay small polarity inversion

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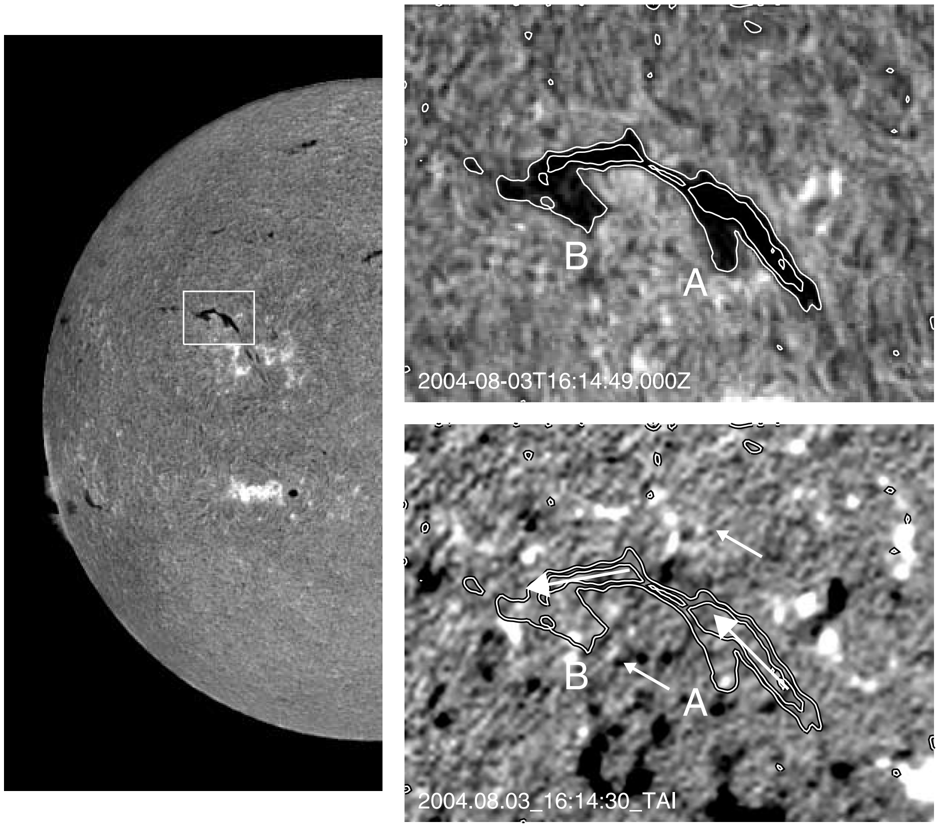

FIG. 1.—Full-disk Hα image of the filament we observed on 2004 August 3 (*left*), its enlargement (*top right*), and the aligned MDI magnetogram (*bottom right*). The two prominent barbs are marked A and B. The magnetic field intensity between −30 and +30 G has been stretched to fit one byte range of the gray scale.

lines where opposite-polarity flux elements are in close contact and mutual cancellation occurs. This finding supports the notion that magnetic reconnection accompanying the flux cancellation is important in injecting mass, being consistent with the theory of Litvinenko (2000) and the observations of Chae et al. (2000) and Chae (2003). Wang (2001), however, could not locate the precise endpoints of barbs on magnetograms because of the limitation in spatial resolution of the He II image data. More ambiguity is also introduced because it is not certain that the He II λ304 barbs are of the same kind as Hα barbs. Aulanier & Schmieder (2002) showed that filament barbs observed in EUV were different from Hα barbs, being related to different minor polarities, more distant from the major inversion line than those related to Hα barbs. Another recent observational test carried out by Zong et al. (2003) produced a result indicating that the endpoints of two barbs are located between the major polarities and the minor polarities. This conclusion, however, is not obvious to us, since the structures they identified as barbs look like just two of many threads comprising the filament, rather than normal barbs.

More recently van Ballegooijen (2004) studied a barb of a U-shaped filament and found that the barb was associated with a weak network element of major polarity, which is contrary to the results of both Martin & Echols (1994) and Wang (2001). Using a nonlinear force-free magnetic model, he could successfully explain the barb in terms of dips in the field lines, supporting the result of Aulanier et al. (1998) on the basis of linear force-free magnetic models.

Two recent papers of Lin et al. (2005a, 2005b) showed that 65% of ends of barbs were related to network boundaries as represented by flow converging regions, but the fine threads were not rooted at G-band bright points that are assumed to be magnetic elements of strong field. They claimed that the direct relationship with magnetic polarities was not achieved because of the weakness of the magnetic field polarity. They wanted to confirm the idea of Martin & Echols (1994) that threads are rooted in the minor polarities. Unfortunately, a negative correlation left the discussion open.

In the present paper we analyze a couple of barbs in a filament that were well defined in Hα images, and whose terminations could be precisely located without any ambiguity. Our analysis reveals that the termination occurred on the minor-polarity inversion line dividing magnetic elements of the major polarity and those of the minor polarity.

2. OBSERVATIONS AND RESULTS

The filament we observed is marked on the full-disk Hα image shown in Figure 1. This image was taken by the Singer telescope of Big Bear Solar Observatory (Denker et al. 1999) on 2004 August 3. The filament was located on the northern hemisphere of the Sun, inside a filament channel associated with an old active region. The filament has two well-developed barbs, which are denoted A and B in the enlarged subimage. They are right-bearing, so the chirality of the filament is determined to be dextral (Martin 1998). The photospheric magnetogram spatially aligned with the Hα image was constructed by averaging 10 full-disk magnetograms taken by the *SOHO* MDI at a one-minute cadence. One pixel of MDI full-disk magnetograms corresponds to $1''.98$, or 1400 km on the Sun. The alignment of the full-disk Hα image and the full-disk magnetograms were first aligned using the coordinate information in the file headers, and then a fine adjustment was made in the relative translation so that the Hα network features and magnetic network elements appear well correlated.

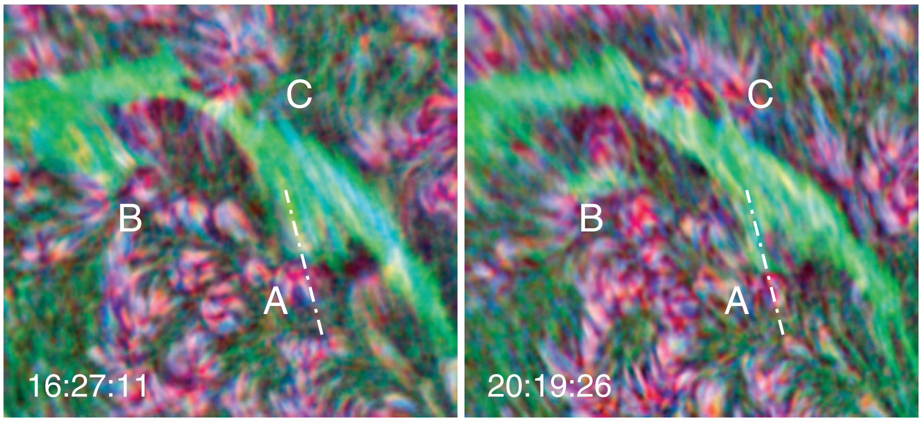

Fig. 2.—Tricolor presentations of Hα −0.6, 0.0, +0.6 Å images. A brighter green means a darker intensity of +0.0 Å images, a brighter blue, that of −0.6 Å images, and a brighter red, that of +0.6 Å images. The filament mainly appears as a green feature, and the network Hα features mostly appear as red, blue, or violet features.

It is obvious from this magnetogram that the filament delineates the polarity inversion line dividing the northern side of positive polarity and the southern side of negative polarity. The direction of the horizontal field of a dextral filament is known to be rightward when viewed by an observer standing in the positive polarity side of the polarity inversion line (Martin 1998). The rough direction of the horizontal field in the filament is represented by the longer arrows, and that of the field in the surrounding chromospheric channel, by the shorter arrows. Note that both the filament field and the chromospheric channel field are nearly parallel to the polarity inversion line.

Now we would like to draw readers' attention to the magnetic field distribution in the two small areas near the ends of two barbs, A and B. The end of barb A is associated with a small bipole that is oriented in the north-south direction. The positive pole is of minor polarity and is smaller than the negative pole of major polarity. The negative pole is one of many network elements in the southern side. A careful comparison reveals an important finding that the barb terminates over a small boundary between the two poles, not over the pole of minor polarity. A similar conclusion may be drawn in barb B, too. The magnetic field distribution in this case is a little complex, being characterized by a couple of strong magnetic elements of minor (positive) polarity and scattered weak elements of mixed polarities. Most of all, it is obvious that the endline of barb B is not over the minor poles. In addition, the endline seems to delineate a small boundary dividing the region of minor polarity (consisting of the two strong elements and much weaker elements) and that of major polarity (consisting of several weak elements).

To strengthen our finding that the barbs terminate over the minor polarity inversion line dividing the parasitic poles of minor polarity and the neighboring fields of major polarity, we present the images constructed from high-resolution Hα observations taken at several wavelengths.

The high-resolution Hα observations were carried out from 15:45 to 24:00 UT on 2004 August 3 at Big Bear Solar Observatory using the 10 inch refractor equipped with a Zeiss Hα filter of 0.25 Å bandwidth. The filter was successively tuned to the five wavelengths at Hα −0.6, −0.3, 0.0, +0.3, +0.6 Å. A fast 1024×1024 CCD camera (DALSTAR 1M30P) made by the Dalsa Corporation was used to grab images at a rate of 30 frames per second. One pixel of the camera corresponds to $0\farcs375$ or 270 km on the Sun. The technique of frame selection was applied, so that only one image was saved every a few seconds. It took about 20 s to finish one cycle of wavelength scan. In the present paper only the initial results are given, and more results from thorough data analysis will be reported in subsequent publications.

Figure 2 shows the color images constructed from Hα images at the three wavelengths −0.6, 0.0, and +0.6 Å. In these images the filament appears as a green feature, and network Hα features have either red, blue, or violet color, so that it is easy to examine the spatial relationship of the filament and network features.

A careful comparison of the color image taken at 16:27 UT with the magnetogram in Figure 1 can reveal that the Hα network features have an one-to-one correspondence with the magnetic elements. It is clear from the two images that the end of barb A is very close to an Hα network feature of negative polarity. But the barb is not connected to this network feature, as can be seen from the sharp intensity discontinuity existing between them. A slight intensity increment of the barb (as denoted by white or yellow color) near its end corresponds to the minor pole. In the case of barb B, it is clearer that the endline of the barb separates the dark red/violet colored poles of major polarity and the bright colored poles of minor polarity. This strongly supports our finding that the barb terminates over the small polarity inversion line dividing the magnetic element of major polarity and the magnetic element of minor polarity.

A couple more things need to be mentioned from Figure 2. We observed a series of protrusions appearing at the region C in the other side of the filament. If barbs are simply defined as lateral protrusions from the filament body, these may merit the name of "barb." But barbs, as currently used, usually refer to lateral extrusions that have strong connection to the chromosphere. It is not clear whether these protrusions have strong connection to the chromosphere or not. In addition, these protrusions are much shorter lived than barbs A and B. Therefore, there is a possibility that they may be different from barbs A and B. So in the present study we exclude these extrusions from our investigation of the relationship between barbs and magnetic fields.

A more important finding comes from the comparison of the two images in Figure 2 that were taken at about a 4 hr interval. We find that the barbs existed more than 4 hrs, keeping roughly the same morphology. In particular, the end of barb A stayed at about the same area as if it was anchored, even though the fine structures were continuously changing during the same period. This suggests that the end of the barb was quite stable. The end of barb B, on the other hand, moved a little bit. As we shall see, this change of the location is related to the change of

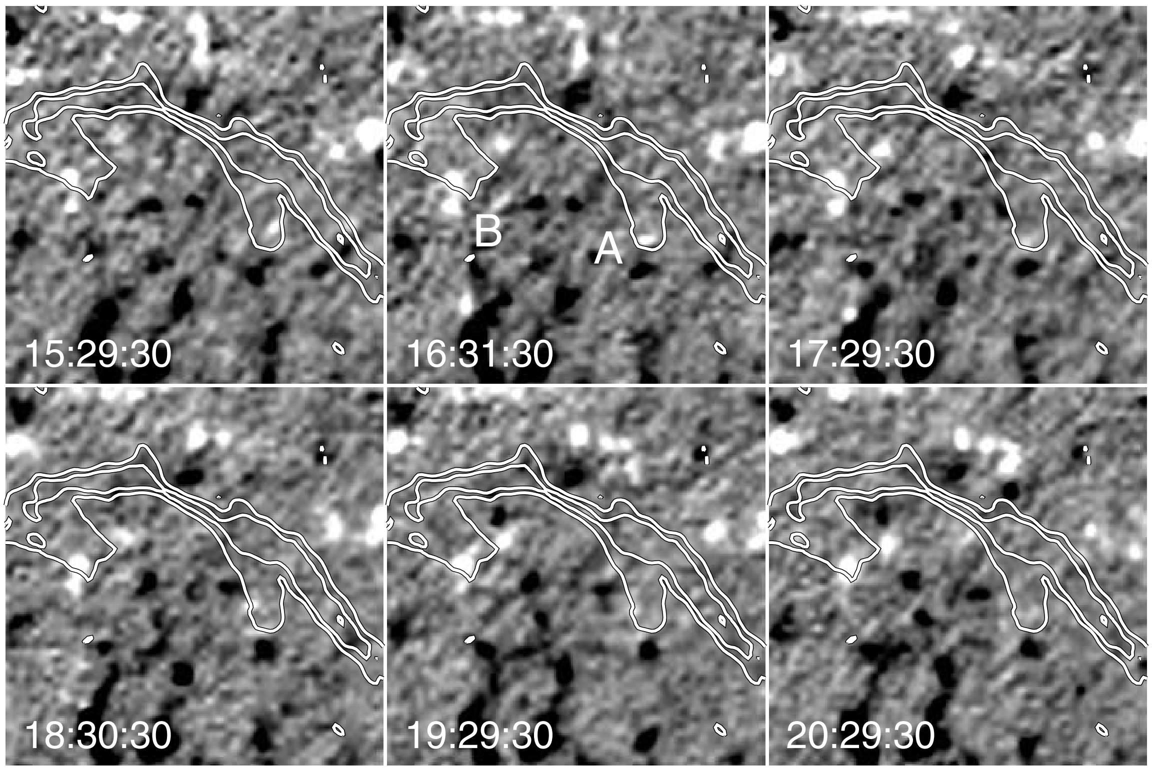

FIG. 3.—Several-hour evolution of the magnetic field near the barbs of the filament. Note the filament shown here for comparison was imaged at 16:14:49 UT.

the magnetic field in the photosphere. It is also noteworthy that in the 20:19 UT image the end of barb B displays stronger Hα absorption than the other part of the barb, implying more Hα absorbing matter.

Figure 3 presents a series of magnetograms taken at different times. This figure clearly shows that the small polarity inversion line below the end of barb A was formed by the converging motion of a small pole of minor (positive) polarity toward the pole of major polarity. The converging motion resulted in the cancellation of the flux and then the disappearance of the minor pole. Long after 17:30 UT only the negative pole remained. Therefore, if the comparison is made between the Hα image and the magnetograms taken long after 17:30 UT, it is not possible to find any minor pole or small polarity inversion line that spatially matches the end of barb A. The only feature that would turn out to be clearly associated with the end of the barb is the network element of major polarity.

In the case of barb B, the barb end is located above the minor polarity inversion line dividing the larger magnetic elements of minor (positive) polarity and the smaller elements of major (negative) polarity. The time series of magnetograms indicates that the flux cancellation proceeded in this polarity inversion line, too. After 19:30 UT, the initial small elements of major polarity almost disappeared, so that the only magnetic feature that is associated with the end of barb B is the magnetic elements of minor polarity. Nevertheless the barb end is not on the minor polarities. A very careful comparison of the Hα image taken at 20:19 UT (Fig. 2) and the magnetogram taken at 20:29 UT (Fig. 3) suggests that the end of barb B was located over the new polarity inversion line a little coarsely defined by the positive pole of an emerging bipole and a nearby network magnetic element of negative polarity. This means that the location of the small polarity inversion line below the end of barb B changed a little with time because of the change in the photospheric magnetic field. This result is in line with that of Aulanier et al. (1999), who showed that a quasi-static evolution driven by the motions of photospheric magnetic fields is in charge of the lateral displacement of a barb they observed.

3. DISCUSSION

Our observations produced results strongly indicating that barbs do not terminate over magnetic elements of minor polarity, but over minor polarity inversion lines that divide magnetic elements of minor polarity and those of major polarity. Moreover, the results indicate that the polarity inversion lines are the places where flux cancellation proceeded. Our results counter the earlier result of Martin & Echols (1994), but confirm the recent results of Wang (2001) and Zong et al. (2003). From this study we also learned the important lesson that depending on the observing instant, one may or may not identify the spatial coincidence of barb ends and minor-polarity inversion lines. Therefore, a careful study of the relationship between barbs and photospheric magnetic fields requires the knowledge of the history of magnetic fields near the barbs as well as high spatial resolution Hα images precisely aligned with magnetograms.

Our results have a significant physical implication for the magnetic structure of barbs. Figure 4 illustrates our idea of the magnetic configuration of barb A in the vertical plane oriented in the direction represented by the dot-dashed line in Figure 2. The magnetic fields of the filament and its environment high above the surface are predominantly horizontal and directed from the negative polarity side to the positive polarity side, making the filament an inverse polarity one. Near the surface where the minor polarity inversion line is located, the field lines are much distorted from the horizontal direction. A natural outcome of this distortion is the existence of concave field lines forming diplike structures. From the viewpoint of magnetic evolution, these field lines have been generated by magnetic reconnection driven by the

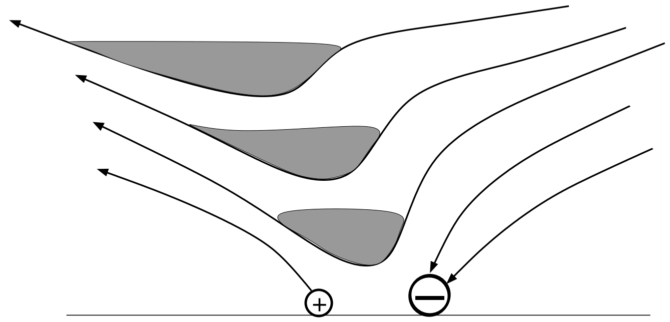

Fig. 4.—Schematic model of the magnetic structure in the plane represented by the dot-dashed line cut in Fig. 2. The cool material suspended in the dips may appear as the observed barbs.

horizonal convergence of two poles. The most favorable place for the lowest level diplike structure to be formed is the region just above the minor polarity inversion line. In this region the dip is spatially confined. This naturally explains why the end of the barb is located above the polarity inversion line. At regions high above the polarity inversion line, the curvature of the field lines becomes small and dips become shallow and horizontally much extended.

An important feature of the model is that none of the field lines supporting filament matter are connected either to the negative pole of major polarity or to the positive pole of minor polarity. This means that the existence of either of the poles may be necessary for the formation of a barb, but is not essential for its maintenance. In this regard we can think of a few variations of the model whose difference mostly reflects the initial condition and the evolution stage. In one case only the negative pole of the major polarity is found near the end of the barb, since the positive pole disappeared; in the other case vice versa. We can even envision the configuration in which none of the poles exist below the barb. These variations may explain the existence of barbs that are not clearly associated with minor polarities, as studied by van Ballegooijen (2004).

A limitation of our study lies in the small number of the barbs examined. It will be necessary to carry out an extended study with a large number of filaments and barbs. We emphasize that to obtain reliable statistical results, the history of magnetic fields should be carefully examined in each of the barbs on the basis of high-sensitivity magnetograms taken simultaneously and precisely co-aligned with high spatial resolution Hα images.

We would like to thank John Varsik, Sergey Shumko, and Randy Fear for their kind assistance in the observations. The referee's constructive comments are greatly appreciated. This work was supported by the Korea Research Foundation Grant (KRF-2002-015-CS0020).

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