Solar Phys (2008) 249: 75–84
DOI 10.1007/s11207-008-9176-x

A Study of Surges: II. On the Relationship between Chromospheric Surges and Coronal Mass Ejections

Yu Liu

Received: 13 April 2007 / Accepted: 14 March 2008 / Published online: 12 April 2008

Abstract Liu *et al.* (*Astrophys. J.* **628**, 1056, 2005a) described one surge – coronal mass ejection (CME) event showing a close relationship between solar chromospheric surge ejection and CME that had not been noted before. In this work, large Hα surges (> 72 Mm, or 100 arcsec) are studied. Eight of these were associated with CMEs. According to their distinct morphological features, Hα surges can be classified into three types: jetlike, diffuse, and closed loop. It was found that all of the jetlike surges were associated with jetlike CMEs (with angular widths $\leq$ 30 degrees); the diffuse surges were all associated with wide-angle CMEs (*e.g.*, halo); the closed-loop surges were not associated with CMEs. The exclusive relation between Hα surges and CMEs indicates difference in magnetic field configurations. The jetlike surges and related narrow CMEs propagate along coronal fields that are originally open. The unusual transverse mass motions in the diffuse surges are suggested to be due to magnetic reconnections in the corona that produce wide-angle CMEs. For the closed-loop surges, their paths are just outlining stable closed loops close to the solar surface. Thus no CMEs are associated with them.

Keywords Sun: chromosphere · Sun: surges · Sun: coronal mass ejections

1. Introduction

Hα surges are chromospheric activities frequently associated with evolving magnetic fields (Roy, 1973). They represent the sudden release of energy in a localized low atmosphere (Martin, 1989). They usually show transient jetlike motions, have maximum speeds of about 50 – 200 km s^{-1}, and reach maximum lengths of typically (5 – 20) × 10^4 km on a time scale of 10 – 20 minutes. The numerical simulation by Yokoyama and Shibata (1995) revealed that X-ray jets and Hα surges are, respectively, the hot and cool components of ejection events resulting from magnetic reconnection in the low solar atmosphere. Emerging flux is though to play a role inducing reconnection with pre-existing coronal magnetic fields. The

Y. Liu (✉)
Institute for Astronomy, University of Hawaii, 34 Ohia Ku Street, Pukalani, HI 96768, USA
e-mail: lyu@ifa.hawaii.edu

reconnection at the interface of rising loops and existing coronal loops heats the plasma to X-ray temperatures. At the same time, the cool chromospheric plasma of the emerging loops is ejected by the tension force of disconnected magnetic field lines. In this sense, the morphology of an Hα surge should be closely related to its ambient coronal magnetic field, which will control the distinctive directions in which the surge plasma moves.

What is the relationship between surges and coronal mass ejections (CMEs)? The hot components, appearing as bright sharp jets seen in EUV or SXR wavelengths, have been studied for their relation to narrow coronal mass ejections (Wang *et al.*, 1998; Wang and Sheeley, 2002; Ko *et al.*, 2005). The outflow of the hot plasma, the speed of which exceeds the local escape speeds, may directly develop into a white-light jetlike CME (Wang *et al.*, 1998).

Hα surges are the cool components of magnetic reconnection events. Although surges have been comprehensively studied for about 70 years, no clear observational evidence has been found linking them with CMEs. With the case study of 16 April 1998 (Liu *et al.*, 2005a), we established the first relation between an Hα surge and a CME. In that study, a surge driven by emerging flux was found to be closely associated with a jetlike CME in both time and space.

As a follow-up to the study of Liu *et al.* (2005a), we collected 10 large Hα surge events from our current database, as well as published examples. In this work, we investigate whether the Hα surges are connected with CMEs. We find a close relationship between different types of surges and different coronal responses.

2. Data and Observations

The Hα data were taken by the Flare Monitoring Telescope (FMT) of Hida Observatory (Kurokawa *et al.*, 1995) and the instruments of the Global High-Resolution Hα Network organized by Big Bear Solar Observatory (BBSO) (Steinegger *et al.*, 2000). The surge events are selected on their maximum length being longer than 100″ (1″ = 726 km). This characteristic assures the clear identification and accurate measurements of the surges and their topology. Since the FMT surges are identified with the criteria set up (Liu *et al.*, 2005b) for the automatic detection of surges, then, the surges studied have no associated filament eruptions. The surges are also confirmed by using EUV and SXR observations for their hot components. These observations were made with the *Solar and Heliospheric Observatory* (SOHO) Extreme ultraviolet Imaging Telescope (EIT) (Delaboudinière *et al.*, 1995) and the *Yohkoh* Soft X-ray Telescope (SXT) (Tsuneta *et al.*, 1991). Every surge event was examined for its CME counterpart. The CMEs were observed with the SOHO Large Angle and Spectrometric Coronagraph (LASCO) (Brueckner *et al.*, 1995).

We have presently found eight surges with CME associations (see Nos. 01 – 08 in Table 1). Two surges (09 and 10), also presented in Table 1, are used as examples for the common surges that are usually observed without CME associations. Of these surges, 01 has been described in detail by Liu *et al.* (2005a); 03 has been presented as a soft X-ray ejection associated with a narrow CME (Kim *et al.*, 2005); and 07 has been described as a "sweeping closed-loop surge" (Wang *et al.*, 2001) as the Hα ejections have irregular individual transverse velocities that cause the surge components to move forward along obvious bifurcating paths. The observations were based on high-resolution BBSO Hα data. The other surges were selected from the Catalog of Outstanding Events by Hida Observatory.

We classify Hα surges into three categories based on their size and trajectory features. Figure 1 illustrates the three types of Hα surges. They are described by two parameters,

Table 1 Parameters of the Hα surges.

Event	Hα surge				
No. – Date	Shape	Location – Start	$\bar{v}$ (km s^{-1})	α	θ_{max}
01 – 16/04/1998	jetlike	N31W26 – 01:05	105 ± 5	14°±2°	25°±1°
02 – 25/08/1999	jetlike	S27E12 – 01:34	140 ± 10	9°±1°	10°±1°
03 – 26/10/2000	jetlike	N15W80 – 04:43	…	16°±4°	16°±4°
04 – 24/12/2001	jetlike	S13E69 – 00:27	360 ± 10	15°±3°	16°±3°
05 – 04/11/1997	diffuse	S18W39 – 06:00	200 ± 8	…	180°±5°
06 – 17/02/2000	diffuse	S25W01 – 18:55	108 ± 5	…	100°±5°
07 – 21/03/2001	diffuse	S06W70 – 02:31	265 ± 15	…	360°
08 – 03/08/2005	diffuse	S30E50 – 05:00	205 ± 5	…	70°±5°
09 – 23/07/2000	closed-loop	N05E16 – 04:27	175 ± 7	14°±3°	110°±5°
10 – 01/10/2000	closed-loop	S08E26 – 01:54	190 ± 5	20°±2°	60°±2°

Note. The start time (UT) of a surge is decided from Hα movies. The definitions of α and θ_{max} can be seen in Figure 1.

α and θ, representing the angular extent of a surge channel and the angle of view of the whole surge mass, respectively. θ_{max} is the maximum angular extent of a surge (Table 1). As shown in Table 1, the first category of Hα surges is called jetlike because such surges are characterized by $\alpha < 20°$, whereas θ_{max} ranges from 10° to 25°. The second category of Hα surges is called diffuse because these surges do not have valid α values and they appear to be widespread in the observation; the θ_{max} angles are normally larger than 100°. The third category is named closed-loop because the surges here outline closed field systems on the solar surface.

2.1. Jetlike Surges

The first surge event listed in Table 1, 01, has been described by Liu *et al.* (2005a). The three jetlike surge events 02, 03, and 04 are shown in Figure 2, with the pre-surge configuration in Hα (the first column), the surge appearances in Hα (the second column), and the CMEs observed with LASCO/C2 (the third and fourth columns).

For each surge, an obvious bright patch appears at the footpoint, indicating that small-scale magnetic reconnection is taking place. Such reconnection drives the chromospheric mass into the corona. In Hα movies, the ejected material is seen moving in a narrow path away from the bright footpoints. The CMEs were detected in LASCO/C2 (Table 2). They were observed following the Hα surges by a few minutes (03) to half an hour (02 and 04), depending on the location of the surge on the Sun. For example, surge 02 occurred at S27E12, and the corresponding CME was seen ∼ 30 minutes later at ∼ 2.5 solar radii. Surge 04 was located at S13E69, and the corresponding CME was seen ∼ 20 minutes later at ∼ 2.5 solar radii; surge 03 occurred at N15W80, and the corresponding CME was seen only ∼ 5 minutes later at ∼ 2.5 solar radii. The disk center distances from the surge regions were 0.49, 0.94, and 0.98 solar radii for events 02, 04, and 03, respectively.

The CME events following the surges demonstrate well-defined jetlike shapes. In event 03 (on 26 October 2000), the associated CME runs almost in the same direction as the surge, similar to event 01 on 16 April 1998 (Liu *et al.*, 2005a). For the other two events (02 and 04), however, obvious deviations can be seen, although the sources of the two CMEs on the

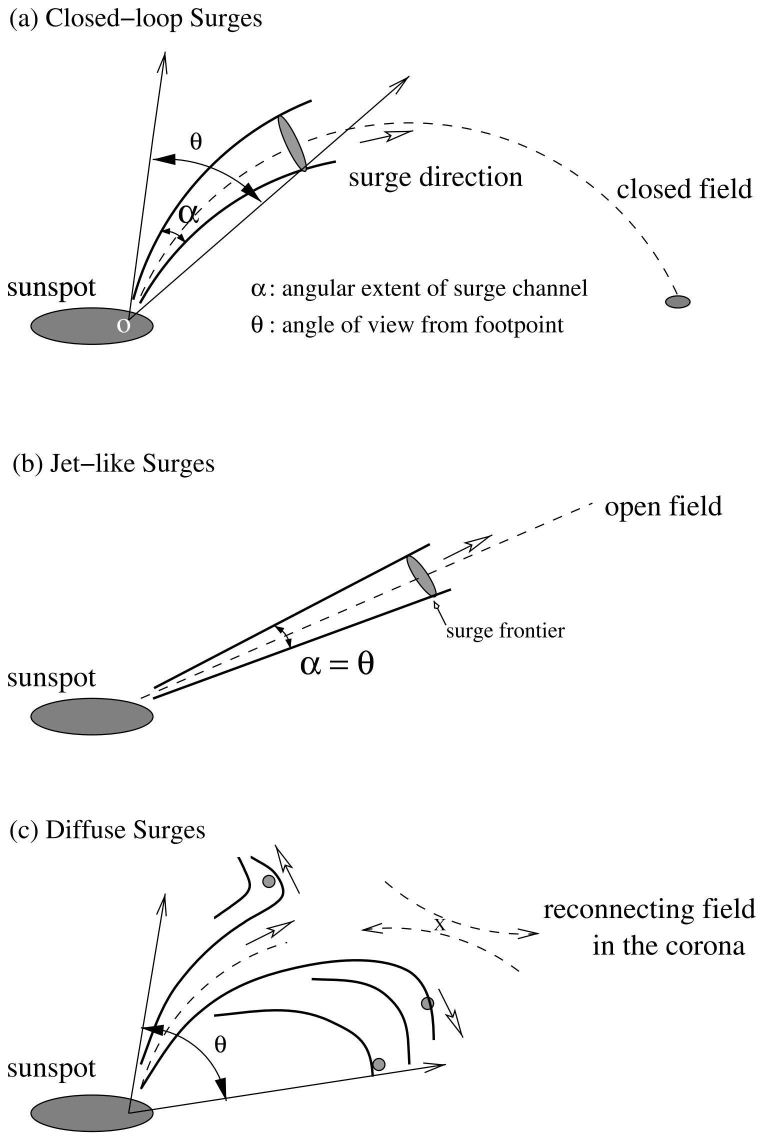

Figure 1 Classifications of large surges based on two-dimensional Hα morphological observations. The parameter α is used for the angular extent of the coronal "channel" that is loaded by dark mass through injection from jetlike and closed-loop surges. Usually, the smaller α is, the denser a surge looks. For diffuse surges, their diffuse features make it impossible to find a reasonable α. θ is the angle of view, for surges at an instant, relative to the surge footpoint. It is measured between two tangent lines that hold the whole ejecta. Since θ is a function of time, the maximum value ($\theta_{\max}$) is listed in Table 1 for comparison. Note that α and θ are both obtained without correcting for projection effects. The dashed lines stand for the deduced direction of the magnetic field, and the thicker solid lines outline the surge channels.

solar surface can still be tracked back to the Hα surge activity regions. The deviations in direction may result from some slight change in the surge path in the 1.1 – 2.0 solar radii range that is below the C2 field of view and for which there are thus no available data. One

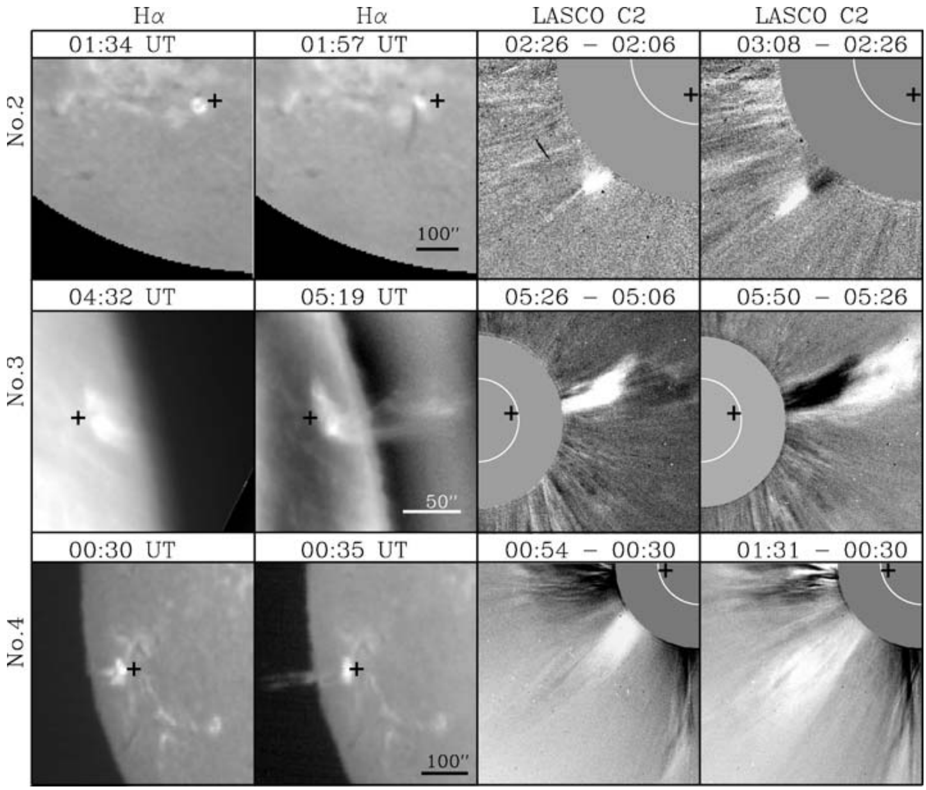

Figure 2 Three jetlike surges. Top: 25 August 1999. Middle: 26 October 2000. Bottom: 24 December 2001. The two left columns are filtergrams in Hα center wavelength. The two right columns are LASCO C2 difference images showing the corresponding CMEs in white light. The plus signs indicate the locations of surge origins on the Sun. For convenience, in this figure and those that follow, the sequence number of every surge event in Tables 1 and 2 is also shown in the left margin.

piece of evidence supporting this assumption is that, in the Hα movie, the far end of the linear path of surge 02 bends slightly toward the solar southeast limb, which is consistent with the accompanying CME direction. We cannot judge whether surge 04 moves in a way similar to 02 since its location is too close to the solar east limb and beyond the FMT field of view. However, the relation between the jetlike CME source regions (plus signs in Figure 2) and the surge areas is clear.

2.2. Diffuse Surges

The diffuse surges are defined as those for which the trajectories are very divergent. The surge body appears whiplike or bifurcated.

In Figure 3, event 05 on 04 November 1997 shows that the surge is moving along an expanding loop that seems to be whipped upward. The event occurred within AR8100 at 06:00 UT following an X1 flare at 05:58:12 UT. A CME appeared at 06:10 UT within the LASCO C2 field of view and developed into a halo CME by 06:44 UT. The image in the last column of the first row shows part of the large-scale EUV dimming on the solar surface, indicating significant mass loss from the solar corona.

Table 2 Parameters of the coronal activities associated with the Hα surges.

Event	CME					EUV plasma
No. – Date	Shape	PA	AW	Start	$\bar{v}$ (km s^{-1})	Shape
01 – 16/04/1998	jetlike	335°	30°	01:55	480	jetlike
02 – 25/08/1999	jetlike	140°	15°	02:06	200	jetlike
03 – 26/10/2000	jetlike	315°	25°	05:26	890	jetlike
04 – 24/12/2001	jetlike	100°	30°	00:54	880	jetlike
05 – 04/11/1997	halo	...	360°	06:10	780	EIT wave
06 – 17/02/2000	halo	...	360°	21:30	730	EIT wave
07 – 21/03/2001	arclike	270°	90°	03:06	330	dimming
08 – 03/08/2005	arclike	105°	65°	05:30	480	EIT wave
09 – 23/07/2000			no CME			closed loop
10 – 01/10/2000			no CME			closed loop

PA: central position angle of the CMEs; AW: angular width of the CMEs. The start time (UT) of a CME is taken from LASCO C2 movies.

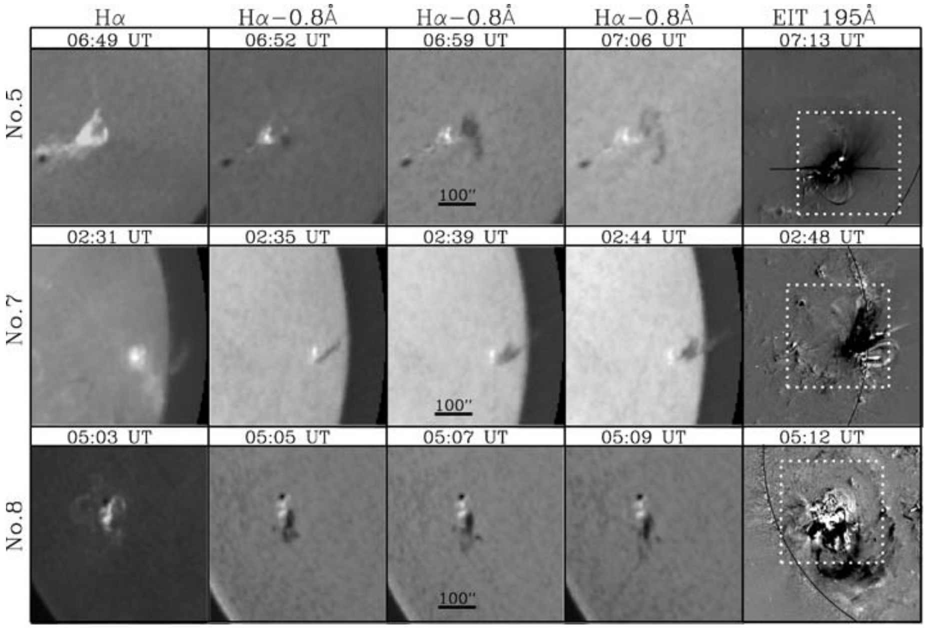

Figure 3 Three diffuse surges. Top: 04 November 1997. Middle: 21 March 2001. Bottom: 03 August 2005. The first column shows the filtergrams in Hα center wavelength, and the second through fourth columns show Hα − 0.8 Å. The last column shows the EIT 195 Å difference images. The dashed boxes indicate the field of view of the Hα images in the figure.

Event 06 on 17 February 2000 is also a diffuse Hα surge associated with an M2.5 flare within AR8869 and 8872 (Wang *et al.*, 2001). The originally compact material of this surge comes from the same region as the flare in the chromosphere, but it subsequently moves into

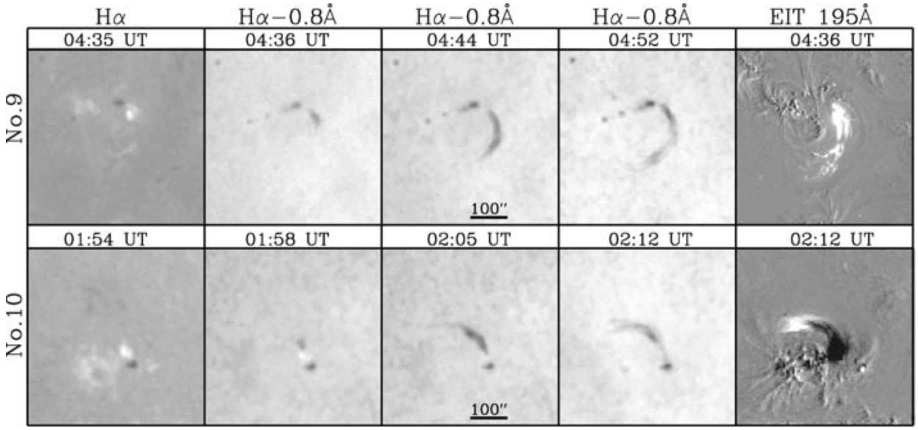

Figure 4 Two closed-loop surges. Top: 23 July 2000. Bottom: 01 October 2000. The first column shows the filtergrams in Hα center wavelength, and the second through fourth columns show Hα − 0.8 Å. The last column shows the EIT 195 Å difference images.

bifurcating paths that quickly branch off the surge material into several strands in the corona. Event 07 on 21 March 2001 has a similar bifurcating structure, but its location is near the solar west limb. The EIT dimming area is mainly localized on the limb, and no EIT wave is detected in the EUV data. A CME launched away from this region emerges as arclike in the LASCO C2 field of view. The bottom row in Figure 3 shows surge event 08 on 03 August 2005. The surge body shows some complicated tearing motions, and its frontier becomes more divergent as the surge ejection continues. This surge is associated with an EIT wave and an arclike CME. In the last frame of Figure 3, there is a noticeable dark closed EIT loop. In fact, it is not a real loop system. It is produced when differencing two EIT images while an EIT wave is progressing southward in this field of view.

The common ground among the diffuse surges is that they are all associated with wider angle CMEs than the jetlike CMEs of the Section 2.1. The mass of the diffuse surges seems to move along more than one dynamic magnetic field system so that their shapes are very irregular relative to other surges.

2.3. Closed-Loop Surges

In our current database containing 40 closed-loop large surges, none of them have CME associations. Because they are well confined in closed loops in the corona, no significant response was expected from the corona in the form of an accompanying EIT wave or a CME. The SXR and EUV movies can be found in the LASCO CME list online. Two examples of Hα surges are shown in Figure 4. The half-circular paths of the two surges are apparent in both Hα and 195 Å wavelengths. These surges are a good indication of the local coronal fields with two ends rooted in the surface and not opened during the surge activities.

3. Conclusions

We made an attempt to find observational evidence for the relationship between small-scale chromospheric surges and large-scale coronal mass ejections. Large surge events with resolution high enough for this study were collected from the Kwasan and Hida Observatories

FMT database and the BBSO Global High-Resolution Hα Network. From the data, only eight large surges have been found with clear accompanying CMEs, whereas most surges are not associated with CMEs. From the limited samples available, we generalize the observational characteristics for the long surges and CMEs in Tables 1 and 2. All the surges listed were observed to reach a maximum length of more than 72 600 km. The surges with CME associations can be identified either as diffuse or jetlike according to their evolution in the Hα data. The diffuse surges have rather diffuse plasma ejecta that spring from the chromospheric footpoints, reaching all the way from the main path to unpredictable branches or directions. In contrast, the jetlike surges are observed along quite simple straight lines. We find that jetlike surges correspond to jetlike (or narrow-angle) CMEs, and diffuse surges to wide-angle CMEs. Moreover, none of the 40 closed-loop large surges in our current database are found to have CME associations. The two events (09 and 10) near disk center are used to represent the closed-loop surges without CME associations. They are classified as closed-loop surges just because their trajectories are quite smooth, compact, and regular, and they usually follow bright SXR or EUV closed loops projected on the solar surface. From Table 1 it can be seen that two of the four jetlike, diffuse surges occurred within $\pm 45^{\circ}$ of solar disk center, and two were close to the limb.

The parameters (angles α and θ) in Figure 1 are used to estimate the surge path compactness and the surge mass angular extent, respectively. The data in Table 1 show that the closed-loop surges have obviously larger θ_{max} than jetlike surges. The result is reasonable because the paths of closed-loop surges are highly curved. The relatively small α indicates a common characteristic for both closed-loop and jetlike surges (*i.e.*, the fall-back trail for mass is almost identical to the original trail for ascent). However, the paths of diffuse surges are too irregular to yield a measurable α value. In the observations, the diffuse surges can show whiplike, bifurcating, or other complicated diverging motions. Such "strong" surges have not been well studied either theoretically or by using simulations. Based on the observations, it is believed that the expanding material in a diffuse surge should be moving along many dynamic paths rather than a single stable one. Obviously, the diffuse surges in Table 2 have strong accompanying coronal activities, such as major flares, EUV dimming, and EIT waves. It is therefore not surprising that diffuse surges are associated with CMEs.

How can we understand the relationship between large surges and CMEs? It is well known that Hα surges are transient dynamic activities involving the chromospheric ejection of plasma. Magnetic cancellation at the base of a surge can be evidence of magnetic reconnection as the driver of surge plasma ejections (Liu and Kurokawa, 2004; Jiang *et al.*, 2007). Because of the low plasma β value (the ratio of the gas pressure to the magnetic pressure) in the low corona, the surge plasma path should clearly depict the magnetic field lines in the corona since the coronal magnetic field controls the plasma motions under the frozen-in conditions. Closed-loop surges are surely valuable for revealing closed fields after energy release in the surge. However, since closed-loop surges cannot get away from the confining fields, they should not be associated with a CME. Jetlike surges should indicate the preexistence of open fields close to the site where magnetic reconnection occurs. The CMEs following jetlike surges are possibly formed directly from the surge mass ejection with speeds above the escape velocity on the solar surface. This conclusion is based on the observations that these CMEs are rather narrow and are launched away from the source regions where jetlike surges originate. This has been confirmed by the fact that some narrow white-light CMEs originate from the high-speed leading edges of some limb EUV jets (Wang *et al.*, 1998). In this paper, jetlike surges in Hα data supply us with additional evidence from the cool temperature observations for studying the trigger mechanism of narrow CMEs. The complicated diffuse surges can be evidence of magnetic reconnection in the corona that gives rise to or accompanies major flares and halo CMEs; thus, the bifurcating and widespread motions in diffuse surges are probably caused by magnetic reconnection in the high corona. As shown in the numerical simulations of the flare breakout model (*e.g.*, Antiochos, DeVore, and Klimchuk, 1999), the sheared photospheric magnetic flux near the magnetic neutral line can burst out after removing the unsheared fields above it by reconnection in the higher corona. The reconnected field lines loading the surge mass can result in the bifurcating morphology for the surge. Similarly, the cause of a whiplike, diffuse surge can be explained with the flux rope eruption model (*e.g.*, Lin and Forbes, 2000). Recalling a whiplike surge of 4 November 1997, which resembles an erupting flux rope, we expect that diffuse surges would occur in the active regions with highly sheared or twisted magnetic flux. The emerging flux is a well-known trigger for Hα surges to inject dense chromospheric mass into the corona, but the ambient coronal field situation including its MHD processes will give rise to the special morphology for a surge. A two-step reconnection process is implied for diffuse surges. The first-step reconnection occurs in the chromosphere owing to emerging flux and it drives the dense mass into the corona, just like for closed-loop surges and jetlike surges. The classical model for the first-step reconnection in the lower atmosphere can be found in some early studies (*e.g.*, Kurokawa, 1988; Shibata *et al.*, 1992; Kurokawa *et al.*, 1993; Schmieder *et al.*, 1995). The second-step reconnection in the corona can reconstruct the field lines to result in the special extending features for diffuse surges. Such a scenario for the second-step reconnection for the formation of diffuse surges can be explained by using Figures 5(b) and (c) in the study by Sterling and Moore (2001), in which both internal and external reconnections are thought to contribute to the magnetic field line reconstruction in the high corona.

Another question related to this study is why some jetlike and diffuse surges have no observed CME association. This can be due to a projection effect and to the surge location on the disk. Observationally, if a jetlike surge occurs too close to the center of solar disk, then its corresponding limb coronal transient should be weakened in LASCO observations, and such a weakened signal is thus easily lost even in the high-contrast movies. However, if a closed-loop surge without a CME occurs far from disk center and the loop system plane is perpendicular to the plane of the sky (or parallel to our line of sight), then this surge may be mistakenly identified as a jetlike surge. It is noteworthy that none of the surge events analyzed in this work was associated with filament or prominence activity, so the surges have been identified without the ambiguity caused by accompanying filament eruptions. Otherwise, errors would be made since an erupting filament resembles a diffuse surge if those surges with neighboring filaments were not excluded.

Finally, if the close relationship between surges and CMEs can be further confirmed based on larger samples of higher resolution data, then the traditional observations of solar surges can be used to predict the CME production that follows the chromospheric activity. Moreover, it can be used for further prediction of the kind of CME that will be triggered (*i.e.*, narrow or halo).

Acknowledgements The author would like to thank the referee for providing many helpful comments to improve the paper. The author thanks the Kwasan and Hida Observatories, BBSO, SOHO, and *Yohkoh* for the high-quality data supplied. Drs. Jiangtao Su and Vasyl Yurchyshyn are appreciated for supplying the data from the Global High-Resolution Hα Network.

References

Antiochos, S.K., DeVore, C.R., Klimchuk, J.A.: 1999, *Astrophys. J.* **510**, 485.

Brueckner, G.E., Howard, R.A., Koomen, M.J., Korendyke, C.M., Michels, D.J., Moses, J.D., *et al.*: 1995, *Solar Phys.* **162**, 357.

Delaboudinière, J.-P., Artzner, G.E., Brunaud, J., Gabriel, A.H., Hochedez, J.F., Millier, F., *et al.*: 1995, *Solar Phys.* **162**, 291.
Jiang, Y.C., Chen, H.D., Li, K.J., Shen, Y.D., Yang, L.H.: 2007, *Astron. Astrophys.* **469**, 331.
Kim, Y., Moon, Y.-J., Cho, K.-S., Kim, K., Park, Y.D.: 2005, *Astrophys. J.* **622**, 1240.
Ko, Y.-K., Raymond, J.C., Gibson, S.E., Alexander, D., Strachan, L., Holzer, T., *et al.*: 2005, *Astrophys. J.* **623**, 519.
Kurokawa, H.: 1988, *Vistas Astron.* **31**, 67.
Kurokawa, H., Kawai, G.: 1993, In: Zirin, H., Ai, G., Wang, H. (eds.) *The Magnetic and Velocity fields of Solar Active Regions*, *CS*-**46**, Astron. Soc. Pac., San Francisco, 507.
Kurokawa, H., Ishiura, K., Kimura, G., Nakai, Y., Kitai, R., Funakoshi, Y., *et al.*: 1995, *J. Geomagn. Geoelectr.* **47**, 1043.
Lin, J., Forbes, T.G.: 2000, *J. Geophys. Res.* **105**, 2375.
Liu, Y., Kurokawa, H.: 2004, *Astrophys. J.* **610**, 1136.
Liu, Y., Su, J.T., Morimoto, T., Kurokawa, H., Shibata, K.: 2005a, *Astrophys. J.* **628**, 1056.
Liu, Y., Kurokawa, H., Kitai, R., Ueno, S., Su, J.: 2005b, *Solar Phys.* **228**, 149.
Martin, S.: 1989, *Solar Phys.* **121**, 215.
Roy, J.-R.: 1973, *Solar Phys.* **95**, 114.
Schmieder, B., Shibata, K., van Driel-Gesztelyi, L., Freeland, S.: 1995, *Solar Phys.* **156**, 245.
Shibata, K., Ishido, Y., Acton, L.W., Strong, K.T., Hirayama, T., Uchida, Y., *et al.*: 1992, *Publ. Astron. Soc. Japan* **44**, L173.
Steinegger, M., Denker, C., Goode, P., Marquette, W., Varsik, J., Wang, H., *et al.*: 2000, *Geophys. Monogr.* **12**, 617.
Sterling, A.C., Moore, R.L.: 2001, *Astrophys. J.* **560**, 1045.
Tsuneta, S., Acton, L., Bruner, M., Lemen, J., Brown, W., Caravalho, R., *et al.*: 1991, *Solar Phys.* **136**, 37.
Yokoyama, T., Shibata, K.: 1995, *Nature* **375**, 42.
Wang, H., Chae, J., Yurchyshyn, V., Yang, G., Steinegger, M., Goode, P.: 2001, *Astrophys. J.* **559**, 1171.
Wang, Y.-M., Sheeley, N.R. Jr., Socker, D.G., Howard, R.A., Brueckner, G.E., Michels, D.J., *et al.*: 1998, *Astrophys. J.* **508**, 899.
Wang, Y.-M., Sheeley, N.R.: 2002, *Astrophys. J.* **575**, 542.