The Astrophysical Journal, 882:110 (9pp), 2019 September 10
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The Dynamics of AR 12700 in Its Early Emerging Phase. II. Fan-shaped Activities Relevant to Arch Filament Systems

Sihui Zhong\(^1\), Yijun Hou\(^2\), Leping Li\(^1,2\), Jun Zhang\(^1,2\), and Yongyuan Xiang\(^3\)

\(^1\) CAS Key Laboratory of Solar Activity, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, People’s Republic of China
\(^2\) University of Chinese Academy of Sciences, Beijing 100049, People’s Republic of China
\(^3\) Yunnan Observatories, Chinese Academy of Sciences, Kunming 650011, People’s Republic of China

Received 2019 May 23; revised 2019 July 17; accepted 2019 July 22; published 2019 September 9

Abstract

The emergence of active regions (ARs) closely relates to the solar dynamo and dynamical atmospheric phenomena. With high-resolution and long-lasting observations from the New Vacuum Solar Telescope, we report a new dynamic activity phenomenon named “fan-shaped activity (FSA)” in the emerging phase of NOAA AR 12700. The FSAs are clearly observed at H\(_o\) wavelengths and are closely related to the dynamics of the adjacent arch filament system (AFS), including thread deformation and material downward motions. On 2018 February 26, the two most representative FSAs appeared around 05:21 UT and 06:03 UT, respectively, and they first ascended and then decayed within around 10 minutes. At the ascending phase, accompanied by the uplifting of an adjacent AFS, each FSA launches up at one end of the AFS and extends for up to \(~\sim 11\) Mm. At the decaying phase, the FSA gradually vanishes, and material downflows toward the other end of the AFS are detected. After checking the evolution of the magnetic fields of AR 12700, we find that each FSA is located between the end of an AFS and an adjacent magnetic patch with the same polarity and launches at the onset of the collision and compression between these two magnetic patches. We propose that the collision lifts up the AFS, and then the initially compact AFS laterally expands, resulting in the formation of FSA. A cartoon model is proposed to depict the activities.

Key words: Sun: activity — Sun: atmosphere — Sun: chromosphere — Sun: evolution — Sun: magnetic fields

Supporting material: animations

1. Introduction

The emergence of active regions (ARs) is a multi-stage process that includes various complex phenomena (van Driel-Gesztelyi & Green 2015). Magnetic flux tubes emerging through the photosphere will form a series of bipolar, and then the conjugated polarities of each dipole move apart. Eventually, patches with the same polarity may merge to form pore-like features. When rising to the chromosphere, the emerging-flux tubes are traced out by an arch filament system (AFS, Bruzek 1967). The AFS is a dark arch-shaped feature connecting two opposite magnetic polarities of newly emerging bipoles, with an upward motion at their tops and plasma downward motion along their legs. Spadaro et al. (2004) observed the AFS dynamic evolution during the emergence of AR 10050, which showed that the values of both the upflow and downflow velocities of the AFS decreased during the evolution of the AR.

Recently, high temporal and spatial resolution observations have lead to significant progress in research of AR emergence. Data from Hinode/Solar Optical Telescope (Tsuneta et al. 2008) have revealed the nature of flux emergence (Otsuji et al. 2011) and evidenced granular-scale elementary flux emergence episodes during the emergence of AR 11024 (Vargas Domínguez et al. 2012). Observations from Hinode, Interface Region Imaging Spectrometer (De Pontieu et al. 2014), and Solar Dynamics Observatory (SDO; Pesnell et al. 2012) detected various local heating events in a new emerging-flux region of AR 12401 (Toriumi et al. 2017). Several ground-based solar telescopes have also made great contributions. Employing observations of the Vacuum Tower Telescope (VTT; von der Lühe 1998), Xu et al. (2010) performed the first investigation of the vector magnetic field and Doppler velocity in the lower solar atmospheric layers of a young emerging-flux region. González Manrique et al. (2017) analyzed VTT observations of an AFS and presented the decay and convergence of two micropores with diameters of less than one arcsecond in a small emerging-flux region. The Goode Solar Telescope (Goode & Cao 2012) observed the emergence of small-scale flux ropes in the photosphere (Vargas Domínguez et al. 2014) and the chromosphere (Yan et al. 2017). Moreover, several studies of AFS based on spectropolarimetric observations by GREGOR (Schmidt et al. 2012) reported supersonic downflows along the legs of the arch filaments (Balthasar et al. 2016; González Manrique et al. 2018). In our previous work (Zhong et al. 2019), combining observations from the New Vacuum Solar Telescope (NVST; Liu et al. 2014) and the nonlinear force-free field (NLFFF) extrapolation results, we presented the detailed process of interchange reconnections in the center of AR 12700 during its emerging phase.

Extensive numerical simulations have also been performed to model the flux emergence (see the review of Cheung & Isobe 2014 and the references therein), and recent three-dimensional (3D) magnetohydrodynamics simulations have successfully produced an AR based on different emergence conditions (Cheung et al. 2010; Archontis & Hood 2012; Rempel & Cheung 2014; Chen et al. 2017; and references therein). Additionally, combining direct analysis of the numerical data, 3D visualization, and spectropolarimetric synthesis, Moreno-Insertis et al. (2018) identified two types of small-scale emerging magnetic structures in the quiet Sun. The emerging granule-covering flux sheets in their models may match the subarcsecond resolution observations of Centeno et al. (2017).
When magnetic flux emerges from beneath the photosphere, it may reconnect with the preexisting fields, which can heat the local plasma, giving rise to jets and emitting waves that propagate into the corona (Isobe et al. 2008). Surges, the most common dynamic activities in the solar atmosphere, are ejections of cool and dense plasma in the chromosphere. Generally, they eject upward along straight or curved paths at velocities of 10–200 km s⁻¹, reaching heights of 5–100 Mm, and lasting for 10–30 minutes (Shibata 1982; Schmieder et al. 1995; Canfield et al. 1996). Observationally, surges are often found at an emerging-flux region in its earliest stage (Kurokawa & Kawai 1993), or on a light bridge in the well-developed or decaying sunspots (Liu et al. 2014; Robustini et al. 2016; Hou et al. 2017; Tian et al. 2018). It is widely believed that the surge is caused by magnetic reconnection related to flux emergence or flux cancellation, which is supported by observational evidence (Chae et al. 1999; Yoshimura et al. 2003; Liu & Kurokawa 2004; Bharti et al. 2007; Li et al. 2016) and numerical simulations (Yokoyama & Shibata 1995, 1996; Jiang et al. 2011, 2012; Nóbrega-Siverio et al. 2017).

In this paper, we report a new dynamic activity phenomenon, fan-shaped activity (FSA), in the emerging phase of AR 12700 on 2018 February 26. This kind of activity is related to AFS and has a similar appearance to surge but lacks the brightness in the extreme ultraviolet (EUV) channel. We analyze the characteristics and driver mechanism of FSA based on the Hα observations acquired at the NVST and the simultaneous observations from the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012) as well as Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board SDO. At Hα wavelengths, several FSAs are detected that are closely associated with the dynamics of the adjacent AFS, including thread deformation and material downflows. The two most representative FSAs appeared around 05:21 UT and 06:03 UT. They exhibit a rapid evolution, ascending and decaying within a period of about 10 minutes. At the ascending phase, accompanied by the uplift of the adjacent AFS, each FSA rises at one end of the AFS and extends for up to ∼11 Mm. After that, the FSA fades away, with materials falling down toward the other end of the AFS.

Our paper is organized as follows. In Section 2, we describe the observations and data analysis taken in this study. Section 3 investigates the FSA in detail. Finally, we summarize the major findings, discuss the results, and suggest a possible mechanism for the formation of the FSA in Section 4.

2. Observations and Data Analysis

The emerging AR 12700 with a β-configuraion at solar disk location N04W01 was observed by the NVST on 2018 February 26. The instruments currently installed on NVST include the adaptive optics (AO) system, the multi-channel imaging system, and two vertical grating spectrometers (Liu et al. 2014). The imaging system of NVST consists of one channel for the chromosphere (Hα) and two channels for the photosphere (TIO and G-band). The NVST Hα 6563 Å observations adapted in this work were taken from 02:01:00 UT to 06:56:00 UT and covered a field of view (FOV) of 152″ × 151″, with a pixel size of 0″136 and a cadence of 8 s. The NVST Hα images can clearly display the detailed AR emergence process in the chromosphere, including fibril emergence, reconnections between different groups of fibrils, and FSAs. In this work, the two representative FSAs appearing at 05:21 UT and 06:03 UT are studied in detail. In order to figure out the photospheric magnetic field evolution and coronal response during the activities, we have also analyzed the data taken by the HMI and AIA on board SDO. The HMI data adopted here were obtained from 2018 February 25 to 26. The time resolution of the line-of-sight (LOS) magnetograms taken by HMI is 45 s and the spatial resolution is 1″0. The AIA provides simultaneous full-disk images of the multi-layered solar atmosphere with 10 passbands, 7 of which are in the EUV channel and observed with a cadence of 12 s and a pixel size of 0″6. All images observed by the SDO are differentially rotated to a reference time (04:00:00 UT on February 26). Moreover, data from all telescopes and instruments are carefully co-aligned using the AIA images as a reference. According to some features that can be simultaneously detected in SDO/AIA 171 Å, and NVST Hα channels, such as dark fibrils and bright points, the original Hα images are rotated and shifted to be co-aligned with the AIA images. Because AIA images and HMI magnetograms have already been co-aligned, HMI magnetograms, and the processed Hα images are then co-aligned as well.

To derive the horizontal photospheric velocities during the two FSAs, we apply the differential affine velocity estimator (DAVE; Schuck 2006). The DAVE method combines the magnetic induction equation and an affine velocity profile to a windowed aperture of the magnetogram sequence to determine the optical flow of magnetic footpoints. We set the window size as 12 pixels in DAVE, and obtain the velocity field from the difference between two sets of HMI LOS magnetograms with a five-minute interval.

In addition, we create a time-slice plot to obtain the velocity of the downflow. First, we approximate the trajectory of the downward material flow using an arc-sector domain. During the period of the downward motion, we collect the imaging data within the arc-sector domain and store them as a two-dimensional array every 8 s. Then, we merge these arrays into a larger two-dimensional array in chronological order. Finally, we display the final array in a figure (time-slice plot) with its X-axis referring to time and its Y-axis referring to distance. In this manner, the slope of the dashed line connecting each endpoint of the downflow in the time-slice plot indicates the projected downward velocity.

In order to investigate the magnetic configuration of the two FSAs, we use the “weighted optimization” method (Wiegelmann 2004; Wiegelmann et al. 2012) to perform NLFFF extrapolations at 05:24 UT and 06:12 UT on February 26, respectively. We utilize the HMI photospheric vector magnetic fields as the boundary condition. Here, the vector magnetograms are pre-processed by a procedure developed by Wiegelmann et al. (2006) to satisfy the force-free condition. Both NLFFF extrapolations are performed in a box of 288 × 168 × 256 uniformly spaced grid points (104 × 61 × 93 Mm³).

3. Results

With the high-resolution and long-lasting Hα observation of NVST from 02:01 UT to 06:56 UT on February 26, we detect a new interesting phenomenon within the emerging AR 12700, namely FSA. Several FSAs are observed, and they have a similar appearance to the Hα surges reported in Shimizu et al. (2009)
and Robustini et al. (2016). And two FSAs are investigated in detail in the present work (see Figure 1). Each FSA is located at the footpoint of an AFS, which is detected clearly at EUV and \( \text{H}_\alpha \) wavelengths.

The first fan-shaped activity (FSA1) was well-observed from 05:21 UT to 05:35 UT on February 26 (see Figure 2 and animation 1), which was located at the north end of an AFS (AFS1). The northern footpoint of AFS1 was anchored in a positive magnetic patch as shown in panel (a). FSA1 ascended from 05:21 UT to 05:28 UT, peaked at 05:29 UT, and descended from 05:30 UT to 05:35 UT. At the ascending stage of FSA1, small-scale threads spouted out at the north end of AFS1 and swept from west to east, which were projected onto a surface to exhibit a fan-shaped feature. At the peak of the activity (Figure 2(d)), the fan-shaped feature consisted of three threads (which are outlined by white dotted curves) with a maximum projected length of about 5 Mm. At the descending stage of FSA1, shown as panel (e), a distinct downflow was detected from 05:31 UT to 05:34 UT at the other footpoint of AFS1. The averaged velocity of the flow toward the south end was \( \sim 33 \text{ km s}^{-1} \).

To investigate the origin of this FSA, we check the photospheric magnetic field evolution of AFS1 (see Figure 3 and animation 2). The bipole connected by the AFS1 initially

Figure 1. SDO/HMI line-of-sight (LOS) magnetogram (panel (a)), SDO/AIA 171 Å image (panel (b)) and NVST H\( \alpha \) images (panels (c1)–(c2)) displaying the AR 12700 and fan-shaped activities on 2018 February 26. The blue and green rectangles in the panel (a1) indicate the FOV of the FSA1 (panels (c1)–(c2)) and that of FSA2 (panels (d1)–(d2)), respectively. The black and white arrows indicate several AFSs and the fan-shaped features, respectively.
emerged at about 02:00 UT. Then, the positive and negative patches of this bipole drifted northeastward and southwestward, respectively. In the following three hours, these two target patches constantly merged with the surrounding magnetic elements with the same polarities, finally forming the two polarities (P1/N1) connected by AFS1. From 05:00 UT, P1 drifted toward the north patch (P2) and then the collision between P1 and P2 occurred where the FSA subsequently launched. In addition, we calculated the photospheric velocity fields by analyzing the HMI LOS magnetograms with the DAVE method. As shown in panels (b1)–(b2), at 04:12 UT, P1 was approaching P2 with a velocity of \(0.45\) km s\(^{-1}\). And at 05:13 UT, the approaching velocity rose to \(0.5\) km s\(^{-1}\), after which compression and collision between P1 and P2 occurred. Combining the HMI magnetograms and H\(\alpha\) observations, it is clearly shown that FSA1 launched soon after the collision started.

The second fan-shaped activity (FSA2) was observed from 06:03 UT to 06:28 UT (see Figure 4 and animation 3), which launched near the southwestern footpoint of another AFS (AFS2). FSA2 ascended from 06:03 UT to 06:13 UT, peaked at about 06:14 UT, and descended from 06:15 UT to 06:20 UT. At 06:03 UT, accompanied by the uplift of the AFS2, thread-like features began to fan out, forming a fan-shaped feature. At the ascending stage, the number of threads that make up the fan-shaped feature grew and their lengths extended, with the maximum projected length reaching up to ~11 Mm. After that, at the northeastern end of AFS2, materials falling at a velocity of \(32\) km s\(^{-1}\) were clearly detected from 06:15 UT to 06:16 UT (see panel (d)).

Figure 5 displays the photospheric magnetic field evolutions of AFS2 (also see animation 4). The bipole connected by the AFS2 emerged around 18:00 UT on February 25 and the emergence region is outlined by the blue parentheses in Figure 4(a1). Then the bipole connected by the third AFS (AFS3) emerged at 07:34 UT on February 26. They all separated from each other along the northeast-southwest direction. Over the next few hours, these bipoles constantly merged with the surrounding magnetic elements, finally forming the polarities (P3/N3 and P4/N4 in panels (a2)–(a3)) connected by AFS2 and AFS3. Note that P3 combined with P4 as one big magnetic patch soon after their emergence. As shown by the HMI magnetograms and velocity fields in panels (b1)–(b2) at 05:24 UT, N3, N4, and N moved westward at velocities of \(0.23\) km s\(^{-1}\), \(0.22\) km s\(^{-1}\), and \(0.21\) km s\(^{-1}\), respectively. And at 06:13 UT, the velocities rose to \(0.38\) km s\(^{-1}\), \(0.59\) km s\(^{-1}\), and \(0.29\) km s\(^{-1}\), respectively. This indicates that N3 was pushed by N4 to collide with N. Combining the HMI magnetograms and H\(\alpha\) observations, FSA2 was located between N3 and N, and launched at the onset of the collision between these two magnetic patches.
Based on the photospheric vector magnetic fields at 05:24 UT and 06:12 UT, we extrapolate the 3D magnetic fields of AR 12700 using NLFFF modeling. Figures 6(a1) and (a2) show the extrapolation results at 05:24 UT from the top and side views, respectively. It is shown that a set of magnetic field lines connects P1 and N1, corresponding to AFS1; see the green curves in Figures 6((a1)–(a2)). To the north of P1, a bundle of nearly open field lines is rooted at another positive magnetic patch (P2). Figures 6(b1) and (b2) display that, at 06:12 UT, another set of magnetic field lines connects the dipole (N3/P3) located in the inner AR, representing AFS2; see the green curves in Figures 6((b1)–(b2)). Adjacent to N3, a set of magnetic field lines with higher altitudes is located above a negative magnetic patch (N); see the pink curves in Figures 6((b1)–(b2)). To some extent, the extrapolation results are consistent with the observations shown in Figures 2–5.

4. Summary and Discussion

In this paper, we study a new dynamic activity phenomenon, FSA, which appeared in emerging AR 12700 on February 26, using observations from the NVST and SDO. The two most representative FSAs appeared around 05:21 UT and 06:03 UT, respectively. Each FSA manifested as a fan-shaped feature located at the footpoint of an adjacent AFS, extending for up to 11 Mm and lasting for about 10 minutes. At the decaying phase of the activities, the fan-shaped features gradually vanished and a distinct material downward motion was detected on the other end of the relevant AFS. Moreover, the photospheric magnetic field evolution and the horizontal photospheric velocity fields showed that these two FSAs might be associated with the compression and collision between one end of the relevant AFS and an adjacent magnetic patch with the same polarity.
As shown in Section 3, the observed FSAs are similar to surges but actually not surges. First, the plasma of the fan-shaped feature was not ejected from the footpoints as typical surges would be, but rather showed up midway. Second, the observations in the present work have not detected any eruption or brightenings accompanying the FSAs, while typical surges usually coexist with multiwavelength brightenings (Liu & Kurokawa 2004; Nishizuka et al. 2008). Third, the sequence of magnetograms and velocity fields showed that the observed fan-shaped features were related to the compression and collision of different patches with the same polarity. Previously reported H\(\alpha\) surges or chromospheric jets usually are located at the polarity inversion line (Uddin et al. 2012) or mixed polarity region (Shibata et al. 2007; Toriumi et al. 2015).

There may be several possible driver mechanisms of the FSA. In this study we propose two possible interpretations for the FSA formation, one of which is that these two FSAs could result from the compression and collision between two magnetic patches with the same polarity. We check the photospheric magnetic field evolution during the FSA1 and find that the northern end of the AFS collided with the northern patches with the same polarity at around 05:16 UT, likely forming a magnetic interface. The magnetic interface was probably where the FSA1 initiated. Likewise, the FSA2 was also associated with the collision between two negative polarities. In addition, at the decaying phases of the FSAs, in the upper atmosphere shown by H\(\alpha\) observations, we find that materials drained down along the legs of AFS with a projected velocity of up to 33 km s\(^{-1}\), which is comparable to the observations in González Manrique et al. (2018). Previous H\(\alpha\) observations focusing on AFS detected downflows at their endpoints, with velocities in the range of 10–50 km s\(^{-1}\) (Bruzek 1969; Spadaro et al. 2004; Zuccarello et al. 2005). The downflow indicates the effect of gravity, supporting the idea that the AFS, which is carrying the materials, has been lifted up. Combining the observations and the NLFFF extrapolation results, we interpret the FSAs as a result of the deformation and uplifting of one leg of AFS, and posit that they are triggered by the collision and compression between the end of the AFS and an adjacent magnetic patch with the same polarity.

To better illustrate this collision model, we sketch several cartoons for the case of FSA1 in Figure 7. At the beginning, the AFS is stable, connecting the opposite polarities (P1 and N1) of a bipole. Then, the positive patch (P1) of AFS shifts northeast and collides with the northernmost positive patch (P2). Therefore, some magnetic field lines of AFS are deformed and lifted up by the magnetic compression. At the north end of

![Figure 4. NVST H\(\alpha\) images from 06:00 UT to 06:15 UT on February 26 displaying the second fan-shaped activity. The black and white curves are contours of the negative and positive polarities at −150 G and +150 G levels, respectively. The black arrows label the second AFS (AFS2) and the third AFS (AFS3). The red rectangle in panel (a) indicates the FOV of panels (b)–(c). The white dotted curves in panels (b) delineate the threads that make up the second fan-shaped feature. The blue arc-sector domain “C–D” covers a dark thread of AFS2 and was used to made the time-slice plot in panel (d). The white dashed line in panel (d) indicates the velocity of the downflow. The online animation displays the second fan-shaped activity at H\(\alpha\) wavelengths shown in Figure 4. The 12 s animation covers 38 minutes from 05:58 UT to 06:36 UT on 2018 February 26.](image-url)
AFS, the initially compact AFS expands laterally, shaping a fan-shaped feature. Another factor contributing to the FSA formation may be that the plasma is blocked by the magnetic interface, then piled up, and the density is increased and hence visible at Hα wavelengths. In addition, materials in the fields of AFS fall down to the south end (N1) because of the action of gravity.

Photospheric magnetic properties including flux emergence, flux cancellation, magnetic reconnection, and shearing are closely associated with different solar activities (Zhang et al. 2001, 2007; Vargas Domínguez et al. 2012; Chintzoglou et al. 2015; Kumar et al. 2017; Hou et al. 2018). Recent observations of Chintzoglou et al. (2019) revealed that collisional shearing, a process during which the collision between unconjugated polarities of multiple bipoles results in shearing and flux cancellation, leads to major solar activities. In the present work, the collision between the same polarities and the effects of this collision are investigated. This type of collision may drive the dynamic evolution of AFS, and then result in the formation of FSA, which were observed for the first time.

In addition, FSA may also be the result of the reconnection occurring between the AFS and its overlying fields. Previous studies have revealed that an emerging-flux tube can reconnect with the preexisting magnetic fields, giving rise to jets or flares (Guglielmino et al. 2010; Vargas Domínguez et al. 2014; Yan et al. 2017). Su et al. (2018) reported that five sequential flares are caused by 3D magnetic reconnection at the quasi-separatrix layers associated with the AFS during the emerging phase of AR 12396. In our case, there are no brightenings detected in the EUV and Hα channels. Thus, the reconnection here might be

![Figure 5](image.png)

**Figure 5.** Sequence of SDO/HMI magnetograms displaying the magnetic evolution, and focusing on the AR. In panels (a1)–(a3), the blue parentheses highlight the bipole connected by the AFS2. The emerging negative magnetic patches are denoted by arrows with different colors. The green rectangle in panel (a3) indicates the FOV of panels (b1)–(b2). In panels (b1)–(b2), the colored arrows represent the velocity fields, which are only plotted on regions where the field strength is stronger than –300 G. The online animation displays the photospheric magnetic field evolution, focusing on the target region shown in Figure 5. The 25 s animation covers 12.5 hr from 18:00 UT on February 25 to 06:32 UT on 2018 February 26.

(An animation of this figure is available.)
Figure 6. Magnetic structures revealed by the NLFFF extrapolations for FSA1 (panels (a1)–(a2)) and FSA2 (panels (b1)–(b2)). The photospheric vertical magnetograms ($B_z$) are shown as the background. The upper panels show the top view of the structures, with north as up and west to the right. The lower panels correspond to the side view. The green curves represent the magnetic connectivity of AFSs (AFS1 and AFS2) and the pink curves represent the magnetic fields of P2 and N.

Figure 7. Cartoon model illustrating the driver mechanism of the first fan-shaped activity shown in Figure 2. Panel (a): the magnetic field configuration before the collision. “P1/N1” denotes the positive or negative polarity connected by AFS1 and “P2” denotes the north patch with the positive polarity, as shown in Figure 3(b1). The green solid curves represent the magnetic connectivity of AFS1 and the pink dashed curves represent the magnetic fields of P2. The blue arrow indicates the shifting direction of P1. Panel (b): the initiation of fan-shaped activity due to the collision between the magnetic elements with the same polarity. The red arrow denotes the lifting direction of the field lines. Panel (c): the peak of the FSA1 as shown in Figure 2(d). The solid curves on the light-blue surface represent the threads that make up the fan-shaped feature as described in Section 3. The green arrow denotes the direction of the plasma downward motion.
We thank the unknown referee for various comments that helped us to improve the manuscript significantly. The data are used courtesy of the NVST and SDO science teams. SDO is a mission of NASA’s Living With a Star Program. This work is supported by the National Natural Science Foundations of China (11533008, 11790304, 11903050, 11773039, 11673035, 11673034, 11873059, and 11790300), and Key Programs of the Chinese Academy of Sciences (QYZDJ-SSW-SLH050).

**ORCID iDs**

Sihui Zhong [https://orcid.org/0000-0002-5606-0411](https://orcid.org/0000-0002-5606-0411)

Yijun Hou [https://orcid.org/0000-0002-9534-1638](https://orcid.org/0000-0002-9534-1638)

Leping Li [https://orcid.org/0000-0001-5776-056X](https://orcid.org/0000-0001-5776-056X)

Yongyuan Xiang [https://orcid.org/0000-0002-5261-6523](https://orcid.org/0000-0002-5261-6523)

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Zhong et al. [https://orcid.org/0000-0001-5776-056X](https://orcid.org/0000-0001-5776-056X)