New Astronomy 26 (2014) 23–32

Contents lists available at SciVerse ScienceDirect

New Astronomy

journal homepage: www.elsevier.com/locate/newast

Downflow-induced brightening following a filament eruption

Zhike Xue [a,c,*], Xiaoli Yan [a,b], Zhongquan Qu [a], Li Zhao [d]

[a] National Astronomical Observatories of China/Yunnan Astronomical Observatory, Chinese Academy of Sciences, Kunming, Yunnan 650011, China
[b] Key Laboratory of Solar Activity, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
[c] University of Chinese Academy of Sciences, Beijing 100049, China
[d] Yunnan Normal University, Kunming 650092, China

ARTICLE INFO

Article history:
Received 7 December 2011
Received in revised form 17 April 2013
Accepted 18 April 2013
Available online 28 April 2013

Communicated by W. Soon

Keywords:
Sun: filaments
Sun: activity
Sun: magnetic fields
Sun: oscillations
Sun: corona

ABSTRACT

The plasma from solar filament eruptions sometimes falls down to the lower solar atmosphere. These interesting events can help us to understand the properties of downflows, such as the temperature and the conversion between kinetic energy and thermal energy. We analyze the case of a filament eruption in active region NOAA 11283 and brightening caused by the return of filament material on September 7 and 8, 2011, observed by the Atmospheric Imaging Assembly (AIA) and the Helioseismic and Magnetic Imager (HMI) aboard the Solar Dynamics Observatory (SDO). Magnetic flux cancellation was observed as a result of the eruption after the eruptive filament started to ascend. Another filament near the eruptive filament was disturbed by an extreme ultraviolet (EUV) wave that was triggered by the eruptive filament, causing it to oscillate. Based on coronal seismology, the mean magnetic field strength in the oscillatory filament was estimated to be approximately 18 ± 2 G. Some plasma separated from the filament and fell down to the solar northwest surface after the filament eruption. The velocities of the downflows increased at accelerations lower than the gravitational acceleration. The main characteristic temperature of the downflows was about 5×10^4 K. When the plasma blobs fell down to lower atmospheric heights, the high-speed downward-travelling plasma collided with plasma at lower atmospheric heights, causing the plasma to brighten. The brightening was observed in all 8 AIA channels, demonstrating that the temperature of the plasma in the brightening covered a wide range of values, from 10^5 K to 10^7 K. This brightening indicates the conversion between kinetic energy and thermal energy.

1. Introduction

Solar filaments (or prominences) are made of relatively cool (5000–8000 K) and dense (10^{10}–10^{11} cm^{-3}) plasma (Hirayama, 1985; Foukal, 2004; Liu et al., 2009). They are suspended in the corona and sustained by the magnetic field that emerges from the photosphere. Yan et al. (2011) studied the relationship between filament eruption, flares and coronal mass ejections (CMEs) using statistical methods and found that 96% of filament eruptions are associated with flares and that 53% of filament eruptions are associated with CMEs. However, some CMEs are not detected by near-Earth spacecraft because they are either too small or have low intensities. The idea that filament eruptions and CMEs have similar mechanisms is widely accepted. Many pioneers tried to determine the mechanisms underlying these phenomena by using numerical simulations, and they produced many models to explain the phenomena observed. These models include the magnetic breakout model (Antiochos et al., 1999; Lynch et al., 2004; DeVore and Antiochos, 2008), the tether-cutting model (Moore and LaBonte, 1980; Moore et al., 2001), the catastrophe model (Forbes, 1990; Forbes and Isenberg, 1991), the kink instability model (Hood and Priest, 1979; Titov and Démoulin, 1999) and the torus instability model (Kliem and Török, 2006; Schrijver et al., 2008).

Downflows above post-flare arcades were observed by McKenzie and Hudson (1999) with the soft X-ray telescope (SXT) aboard Yohkoh. These downflows moved to the solar surface from the corona at speeds of 45–500 km s^{-1}. Asai et al. (2004) found some dark downflows above post-flare loops by examining extreme-ultraviolet images taken by the Transition Region And Coronal Explorer (TRACE) and deduced that the downflow motions occurred when strong magnetic energy was released. Innes et al. (2003) reported a series of dark, sunward moving flows using TRACE 195 Å images and concluded that the dark flows are plasma voids. Sometimes, after the eruption of CMEs or filaments/prominences, one can see that plasma from the CMEs or filaments/prominences moves down to a region of the lower solar atmosphere, such as the transition region or even the chromosphere. Wang et al. (1999) reported that small, faint structures moving inward through the corona after CMEs with velocities from less than 20 km s^{-1} to over 1000 km s^{-1}

---

* Corresponding author at: National Astronomical Observatories of China/Yunnan Astronomical Observatory, Chinese Academy of Sciences, Kunming, Yunnan 650011, China. Tel.: +86 871 63920609; fax: +86 871 63920140.

E-mail address: zkxue@ynao.ac.cn (Z. Xue).

1384-1076/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.newast.2013.04.005

were observed by the Large Angle and Spectrometric Coronagraph (LASCO) on board the Solar and Heliospheric Observatory (SOHO). Tripathi et al. (2006) discovered a distinct coronal downflow in the course of a prominence eruption associated with a CME observed by the Extreme-ultraviolet Imaging Telescope (EIT) and by LASCO on board SOHO on March 5, 2000. They found that the downflows consisted of bright coronal plasma and showed a rapid acceleration followed by a strong deceleration. Tripathi et al. (2007) studied this event with the Hα and the MK4 coronagraphs at the Mauna Loa Solar Observatory (MLSO). The coronal downflows could be seen in the EIT, SXT, Hα and MK4 images, which revealed that the downflows consisted of multi-thermal plasma and that their speeds were higher than free-fall speed. Using the projected value and Doppler velocities, which define an orthogonal system, and by calculating them at each time step Zapiór and Rudawy (2010) restored the true three-dimensional trajectories of prominence knots and analyzed three events. They found that the radial velocities of the blobs could reach about 40 km s^{-1}. Liu et al. (2012) calculated the velocities of downflows from a prominence. They found that the velocities had a narrow Gaussian distribution with a mean of 30 km s^{-1} and that the acceleration distribution of downflows displayed an exponential drop with a mean of about 1/6 $g_{\odot}$. The prominence downflows traveled at a velocity much slower than free fall. Liu et al. (2012) proposed that Lorentz forces might counter the gravitational acceleration. Rayleigh–Taylor instabilities were used by Innes et al. (2012) to explain the morphology of downflows that occurred on June 7, 2011, wherein extreme ultraviolet (EUV) brightenings caused by the falling plasma were also observed.

The downflows from CMEs or filaments/prominences appear similar to coronal rain. Coronal rain forms on a timescale of minutes in the hot coronal environment, in the shape of cool and dense blob-like material. On a longer timescale (tens of minutes, depending on the length of the loop), the plasma of coronal rain falls down from the solar corona to the chromosphere, due to gravity. Coronal rain falls at speeds much lower than free-fall along loop-like paths (Schrijver, 2001; De Groof et al., 2004; De Groof et al., 2005; Müller et al., 2005; Antolin and Rouppe van der Voort, 2012). Thus, there are forces other than gravity acting to limit the acceleration of the mass of the coronal rain. Mackay and Galsgaard (2001), Müller et al. (2003) and Antolin et al. (2010), using numerical simulations, suggested that gas and magnetic pressures may be the reasons for the observed deceleration. Antolin and Verwichte (2011) studied coronal rain oscillations observed on November 9, 2006 by the Hinode/Solar Optical Telescope and applied coronal seismology theory to deduce the coronal magnetic field. They found that the observed wave pressure from the transverse wave may also cause a deceleration of coronal rain.

In this paper, we present observations of an active-region filament eruption in NOAA 11283, resulting in downflows at the northwest of the solar disk on Sep. 7 and 8, 2011, and the brightening of the lower solar atmosphere caused by the downflows. We investigate the intrinsic properties of the observed downflows and of the hosting environment. The energy conversion between kinetic energy and thermal energy discussed here may provide insight into some details of the collision process. The organization of this paper is as follows. In Section 2, we present the instrument and data reduction. In Section 3, the analysis method is described. Results are presented in Section 4, while a discussion is presented in Section 5, and the conclusions are provided in Section 6.

2. Observations

The data used in this paper are from the Solar Dynamics Observatory (SDO; Pesnell et al., 2012). SDO is designed to help us understand the Sun by studying the solar atmosphere on small scales of space and time and in many wavelengths simultaneously. More detailed information on the data is listed below.

(1) Coronal images are from the Atmospheric Imaging Assembly (AIA; Lemen et al., 2012) aboard SDO. AIA is an array of 4 telescopes that together provide full-disk images of the solar atmosphere with 1.5 arc-second resolution (4096 × 4096-pixel images) in 10 ultraviolet (UV) and EUV wavelengths every 12 s. The wavelength, region of solar atmosphere and characteristic temperature of each AIA channel are listed in Table 1.

(2) Line-of-sight magnetograms are from the Helioseismic and Magnetic Imager (HMI; Scherrer et al., 2012) on board SDO. HMI provides full-disk, high-cadence Doppler, intensity, and magnetograms with a resolution of approximately 1 arc-second (4096 × 4096-pixel images) of the solar photosphere, allowing for studies of the sources and evolution of activity within the solar interior. The solar full-disk line-of-sight magnetograms are available at the Fe I absorption line at 6173 Å, with a cadence of 45 s.

On 2011 Sep 7, an active-region filament (referred to as F1 hereafter) appeared in the active region NOAA AR 11283, which was a bipolar active region located in the solar northwest (see Fig. 1(a1)–(c1)). At 22:32 UT, a large flare (X1.8) occurred in the active region. At 22:35 UT, F1 started ascending at the same place and finally erupted. An EUV wave appeared in NOAA AR 11283 at 22:35 UT and propagated to the northwest of the active region. Another filament (referred to as hereafter as F2) near F1 began to oscillate at 22:38 UT (see Fig. 2(a)). While ascending to higher altitude, a portion of the material of F1 started falling back to the lower solar atmosphere at more northward areas as another portion of material was ejected in the form of a CME. When the filament matter reached the lower solar atmosphere, the plasma in the collision region became brighter.

3. Analysis

To study the kinematic characteristics of F1, we calculate its height projected onto the plane of the sky along its main ascending direction (white lines in Fig. 1) using a time-slice map. The height of F1 is fitted with a quadratic function from which the velocity, acceleration and their errors are obtained. The mean square error of the quadratic fit is 4.8 km. The progress of the EUV wave is shown more clearly in the running difference images of AIA 193 Å, which are produced by subtracting the images from 24 s earlier. The phase speed of the EUV wave along its propagation path is calculated in a time-slice map. To study the oscillation of F2, we calculate the time-slice map along the oscillation direction of F2 where the maximum of oscillation is located. The intensity

Table 1
The wavelengths, regions of solar atmosphere and characteristic temperatures of each AIA channel. M and S represent the main and secondary characteristic temperature of each channel, respectively.

Wavelength (Å)	Region of solar atmosphere	Char. log (T)
304	Chromosphere & transition region	4.7 (M)
1600	Transition region & upper photosphere	5.0 (M)
171	Quiet corona, upper transition region	5.8 (M)
193	Corona & hot flare plasma	6.2 (M) & 7.3 (S)
211	Active-region corona	6.3 (M)
335	Active-region corona	6.4 (M)
94	Flaring corona	6.8 (M)
131	Transition region & flaring corona	5.6 (M) & 7.0 (S)