

# Multiwavelength Observations of Supersonic Plasma Blob Triggered by Reconnection-Generated Velocity Pulse in AR10808

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**Abstract** Using multi-wavelength observations of *Solar and Heliospheric Observatory* (SoHO)/Michelson Doppler Imager (MDI), *Transition Region and Coronal Explorer* (TRACE, 171 Å), and H $\alpha$  from Culgoora Solar Observatory at Narrabri, Australia, we present a unique observational signature of a propagating supersonic plasma blob before an M6.2-class solar flare in active region 10808 on 9 September 2005. The blob was observed between 05:27 UT and 05:32 UT with almost a constant shape for the first 2–3 min, and thereafter it quickly vanished in the corona. The observed lower-bound speed of the blob is estimated as  $\approx 215 \text{ km s}^{-1}$  in its dynamical phase. The evidence of the blob with almost similar shape and velocity concurrent in H $\alpha$  and TRACE 171 Å images supports its formation by a multi-temperature plasma. The energy release by a recurrent three-dimensional reconnection process *via* the separator dome below the magnetic null point, between the emerging flux and pre-existing field lines in the lower solar atmosphere, is found to be the driver of a radial velocity pulse outwards that accelerates this plasma blob in the solar atmosphere. In support of identification of the possible driver of the observed eruption, we solve the two-dimensional ideal magnetohydrodynamic equations numerically to simulate the observed supersonic plasma blob. The numerical modelling closely match the observed velocity, evolution of multi-temperature plasma, and quick vanishing of the blob found in

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the observations. Under typical coronal conditions, such blobs may also carry an energy flux of  $7.0 \times 10^6 \text{ erg cm}^{-2} \text{ s}^{-1}$  to balance the coronal losses above active regions.

**Keywords** Corona · Flares · Flux tubes · Magnetic fields

## 1. Introduction

Large-scale solar transient phenomena (solar flares, CMEs, and associated eruptions) are examples of magnetically active, dynamical, and highly energetic plasma processes of the Sun during which the energy stored in the sheared, twisted, and highly complex magnetic structures is rapidly released in the form of high energy particle acceleration, plasma heating, and bulk mass motion and eruptions within timescales from a few minutes to a few tens of minutes (Benz, 2008, and references cited there). However, the exact mechanism of the initiation and triggering of solar flares, coronal mass ejections (CMEs), and other associated dynamical processes since the discovery of the first flare by R.C. Carrington on 1 September 1859, is not yet known in full detail both as regards the observations and theory (Fletcher *et al.*, 2011b, and references cited there). It is well explored that the flares and associated eruptions may occur near the magnetic null points, and current sheets are formed by instability near the neutral point where field lines exhibit a magnetic reconnection process, *i.e.*, the rapid dissipation of electric currents (Manoharan and Kundu, 2003; Shibata and Magara, 2011). Reconnection can be an efficient mechanism of converting magnetic energy to thermal and bulk kinetic energies and to accelerate particles, as well as shock heating of the plasma (Benz, 2008; Shibata and Magara, 2011). The novel observational signature of three-dimensional (3D) X-type loop–loop interaction and the flare triggering due to reconnection in an active magnetic complex has recently been reported by Kumar *et al.* (2010a). It is also found that the instabilities (kink, magnetic Kelvin–Helmholtz, coalescence, *etc.*) can also be one of the favourable mechanisms to trigger solar flares with or without CMEs (Liu, Alexander, and Gilbert, 2007; Srivastava *et al.*, 2010; Kumar *et al.*, 2010b; Foullon *et al.*, 2011; Botha, Arber, and Srivastava, 2012). In conclusion, appropriately correlated theoretical and observational studies of these phenomena still need to be explored to understand the complex dynamical processes at the Sun.

In spite of a number of attempts to analyse the energy build-up and energy release processes associated with these eruptive phenomena, the recent trend has also been to study the responses of solar eruptions on the plasma dynamics and the generation of periodic (quasi-periodic) oscillation patterns during these energetic events. These natural responses to the highly energetic solar eruptive phenomena are very useful in diagnosing and constraining the local plasma conditions of the solar atmosphere. The high-speed plasmoids associated with CME eruptions (Sheeley and Wang, 2002; Manoharan and Kundu, 2003; Lin *et al.*, 2005; Riley *et al.*, 2007; Milligan *et al.*, 2010), chromospheric evaporation (Veronig *et al.*, 2010), very high-speed outflows (Wang *et al.*, 2006), down-flows and plasma condensations (Yokoyama *et al.*, 2001) in the course of flaring activities have been extensively studied. Secondary plasmoids may also be involved in the eruptive region due to plasmoid instability in a sufficiently long and thin current layer (Loureiro, Schekochihin, and Cowley, 2007). Therefore, they are associated with reconnection, but not directly with CMEs. The ejecta can only generate the favourable conditions for plasmoid instability by formation of elongated and stretched current sheet in the active region. Periodic and quasi-periodic magnetohydrodynamic (MHD) oscillations have also been observed and studied as a natural response of the solar flares in their vicinity regions (Roberts, Edwin, and Benz, 1983; Aschwanden *et al.*, 1999; Wang *et al.*, 2002; Foullon *et al.*, 2005;

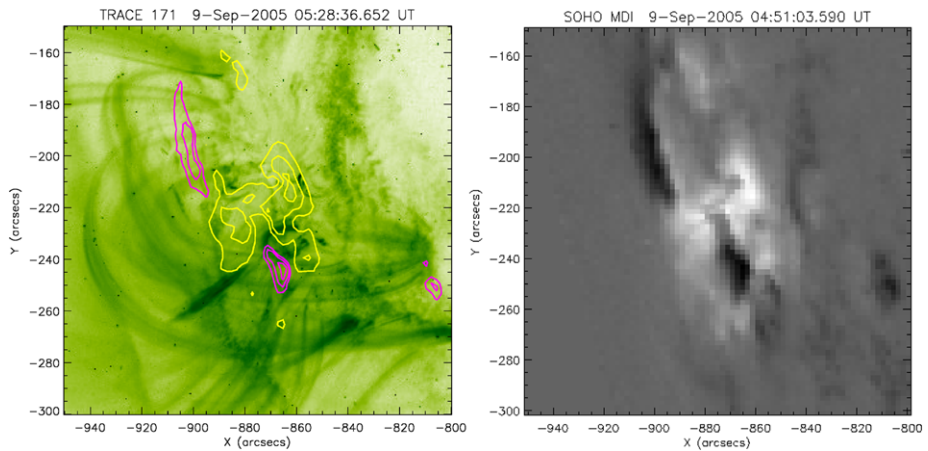
Ballai, Erdélyi, and Pintér, 2005; Nakariakov *et al.*, 2006; Taroyan *et al.*, 2007; Erdélyi and Taroyan, 2008). The energy deposited in these MHD oscillations are found to be orders of magnitude smaller compared to the flare energy release (Terradas, Andries, and Goossens, 2007). On the other hand, flare- and CME-induced waves and oscillations are also very useful to gain first insight into the local plasma conditions and dynamical processes of the active regions (Erdélyi and Verth, 2007; Andries *et al.*, 2009; Aschwanden, 2009; Taroyan and Erdélyi, 2009; Terradas, 2009; Ofman, 2009; Ruderman and Erdélyi, 2009).

In addition to the large-scale motions in terms of flows and ejecta, waves and oscillations of magneto-fluids, and energetics of solar eruptions, the formation of small-scale plasma motions, *e.g.*, anemone jets, spicules, penumbral jets (De Pontieu, Erdélyi, and James, 2004; De Pontieu and Erdélyi, 2006; De Pontieu *et al.*, 2007; Katsukawa *et al.*, 2007; Kumar, Srivastava, and Dwivedi, 2011), and waves in the form of transient pulses and wave packets (Zaqarashvili, Kukhianidze, and Khodachenko, 2010; Murawski and Zaqarashvili, 2010; Srivastava and Dwivedi, 2010) are important in observations to understand the heating and dynamics of the solar plasma at small spatio-temporal scales. These MHD/HD pulses may also be important to power small-scale transients in the lower solar atmosphere (Murawski and Zaqarashvili, 2010). The theory of MHD pulses and wave excitation are established to some degree (Roberts and Webb, 1979; Carlsson, Judge, and Wilhelm, 1997; Selwa and Ofman, 2010; Selwa, Ofman, and Murawski, 2007; Murawski and Zaqarashvili, 2010). However, observational signatures have not been very abundant in past few years to gain an understanding of their role in the excitation of solar transients (*e.g.*, jets at various spatio-temporal scales). On the other hand, the role of magnetic reconnection, twisted flux emergence from sub-photospheric layers, and generation of instabilities are well-studied both in observations and theories in the jet productive regions (Culhane *et al.*, 2007; Nishizuka *et al.*, 2008; Filippov, Golub, and Koutchmy, 2009; Pariat, Antiochos, and DeVore, 2009).

In the present paper, we analyse multi-wavelength imaging data of active region NOAA AR 10808 that has produced violent explosions in the form of giant solar flares and associated eruptions. However, this active region has exhibited a very interesting phenomenon, surprisingly rather quietly before an M-class flare on 9 September 2005, in the form of a supersonic cylindrical plasma blob ejection from the flare site between 05:27 UT and 5:33 UT. The blob was observed in *Transition Region and Coronal Explorer* (TRACE; Handy *et al.*, 1999) 171 Å images and also in H $\alpha$  image sequences captured by Culgoora Solar Observatory, Australia. Information on the magnetic field of the active region was obtained from Michelson Doppler Imager (MDI) on the *Solar and Heliospheric Observatory* (SOHO). We present the observational data in Section 2. A numerical modelling and theoretical interpretations of the supersonic plasma blob is described in Section 3. The results and discussions are given in the last section.

## 2. Observations of Supersonic Plasma Blob

Active region (AR) NOAA 10808 appeared on the east limb on 7 September 2005 and produced at least 10 X-class and 25 M-class solar flares until it disappeared behind the solar disk (Nagashima *et al.*, 2007). The active region was located nearby the eastern limb of the southern hemisphere near the equatorial plane at S10E67 with  $\beta\gamma\delta$  field configuration of the sunspot group. This active region was also associated with CMEs and filament eruptions, and produced numerous space weather activities by its furious eruptive events (Archontis and Hood, 2010; Canou *et al.*, 2009; Nagashima *et al.*, 2007; Wang *et al.*, 2006; Li *et al.*, 2007).

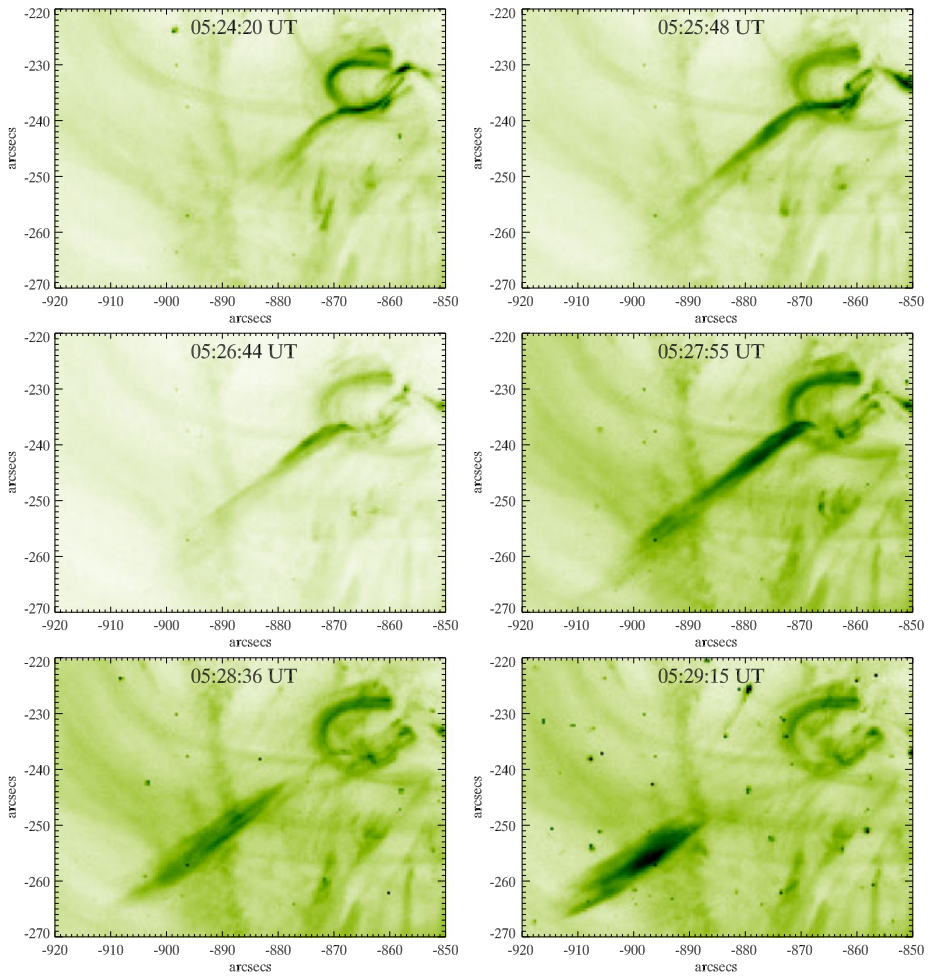


**Figure 1** (Left) Co-aligned MDI contours overlaid on TRACE 171 Å context image of active region 10808 at 05:28:36 UT on 9 September 2005. Yellow (magenta) contours show positive (negative) photospheric magnetic fields, respectively, at levels  $-800$ ,  $-600$ ,  $-400$ ,  $500$ ,  $900$ ,  $1300$  gauss. The plasma blob is shown to be propagating up in the solar atmosphere from its origin site that is associated with maximum magnetic fields. (Right) The observed magnetic field on 04:51 UT, which later came more inside the disk during the transient event.

Figure 1 shows the coronal image of AR 10808 as observed with the TRACE 171 Å filter at 05:28:36 UT on 9 September, 2005. The TRACE image is overlaid by co-aligned MDI contours showing positive (yellow) and negative (magenta) magnetic polarities (left panel of Figure 1). The positive and negative polarities seem to be elongated respectively towards north-west to south-east, and north-east to south-west, with tongue-like structures (*cf.*, right panel of Figure 1). This is a very typical signature of AR10808 and seems to be evidence of the emergence of twisted rising flux (Archontis and Hood, 2010; Li *et al.*, 2007). This typical characteristic of AR10808 was one of the main causes that were responsible for the very energetic flares, CMEs, and filament eruptions, though the rotation of sunspots and the tilt of the bipolar axis were also observed in this active region (Archontis and Hood, 2010; Canou *et al.*, 2009; Nagashima *et al.*, 2007; Wang *et al.*, 2006; Li *et al.*, 2007). Although the violent solar eruptions have been extensively analysed from this active region, we highlight here additional and interesting plasma dynamics during an M-class flare that took place for a short duration of about 5–7 min on 9 September 2005. The M6.2-class solar flare has occurred in AR10808 at the location S10E66. It started at 05:32 UT, peaked at 05:48 UT, and ended at 06:00 UT. The observed short duration plasma dynamics that is the interest and theme of this paper, has occurred well before this M6.2-class solar flare just at the flare brightening site.

## 2.1. TRACE Observations

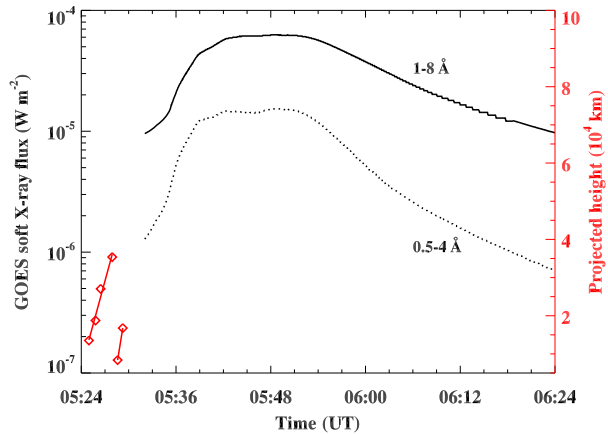
Figure 2 shows the time series of TRACE 171 Å images of the flaring region in AR10808 during the time interval 05:24–05:29 UT. The plasma blob (a dark and dense material) was formed between 05:24–05:27 UT above the flare site, followed by its detachment and propagation upward after 05:27 UT. TRACE has missed the later part of the event, but it was captured by H $\alpha$  observations from Culgoora Solar Observatory. The length and width of the plasma blob, as observed in the TRACE images in its dynamical phase, are approximately 22 Mm and 5 Mm, respectively. The blob was co-spatially and co-temporally visible in the



**Figure 2** Selected series of TRACE 171 Å images (in negative) showing a moving blob structure above the smaller bright loop of AR10808.

TRACE 171 Å and H $\alpha$  (6563 Å) emissions, and finally vanished around 05:33 UT. In the TRACE snapshot at 05:27:55 UT, the tail of the eruptive plasma was rooted at  $(X_1, Y_1) \approx (-867'', -236'')$ , while at 05:28:36 UT it reached at  $(X_2, Y_2) \approx (-880'', -247'')$ . Therefore, the projected distance  $d_{12}$  travelled in  $\Delta t_{12} \approx 41$  s is  $\approx 12\,346$  km. Thus, the approximate apparent speed in the first stage ( $v_1$ ) derived from these two snapshots is  $300$  km s $^{-1}$ . At 05:29:15 UT, the tail of the blob that was almost constant in shape for around 3–4 min, and reached at  $(X_3, Y_3) \approx (-888'', -250'')$ . Therefore, the distance  $d_{23}$  travelled in  $\Delta t_{23} \approx 39$  s is  $\approx 6200$  km. Assuming the  $1'' = 725$  km scale for the conversion, the approximate speed in the second stage ( $v_2$ ) is found to be  $160$  km s $^{-1}$ . Therefore, the average speed of travel is  $v_{av} = (v_1 + v_2)/2 \approx 230$  km s $^{-1}$ . After this the blob quickly vanished in the corona. Note that the measured speeds  $v_1$  and  $v_2$  are projected speeds of the blob by tracing its detached tail, and the actual speeds may be higher compared to the estimated speeds. Also worth illustrating is that these speeds are anyway higher when compared to the local sound

**Figure 3** The GOES X-ray profiles show a long duration M-class flare, and its temporal relation with the rising of the plasma blob. The initiation and dynamical phases of the rising motion of the blob are linearly fitted to derive the projected lower-bound speeds. The linear fit in the initiation phase (05:24–05:27 UT) corresponds to the position of the leading edge of the blob while the fit in the dynamical phase (05:28–05:30 UT) shows the position of its trailing edge.



speed ( $\approx 150 \text{ km s}^{-1}$ , see below). Next, we trace the approximate position of the core of the moving feature in its dynamical phase to find its projected speed as  $\approx 175 \text{ km s}^{-1}$ . Since it is very difficult and somewhat superfluous also to track the diffused and faint head of the moving feature, we only take the references of the core and tail of the blob observed in the TRACE images to estimate the approximate lower-bound speeds. In conclusion, the blob plasma moved almost collectively after its origin and detachment from the flaring site due to reconnection. In the TRACE snapshots during 05:24 UT–05:27 UT, it is clear that there was some interaction between the rising plasma column that has detached later on in the form of a blob and the pre-existing fields. The magnetic field configuration has become simpler (*cf.*, 05:28–05:29 UT snapshots) at the origin's site of the blob after its detachment.

Next, Figure 3 shows the GOES soft X-ray evolution of the M6.2-class solar flare observed in the active region and the corresponding projected time-distance plot of the observed plasma blob. We found that two other eruptions occurred, respectively, at 05:15 UT and 05:50 UT from the same location (see the attached movie trace-eruptions.avi in Online Supplementary Material). However, they are exclusively different from the observed unique plasma blob. Firstly, other eruptions did not propagate in a definite shape of a blob, and secondly they were not visible simultaneously in the cool  $\text{H}\alpha$  temperature. However, the multiple supersonic eruptions from the same location may be a collective signature of repetitive reconnection ongoing at the flare site.

Figure 3 also depicts the linear fit in the projected distance of the travel of the blob as measured from the TRACE image sequence, and it is also given both in its initiation and dynamical detachment phases. The linear fit between 05:24–05:27 UT corresponds to the position of the leading edge of the plasma column and the blob forming inside it in the initiation phase, while the fit at 05:28–05:30 UT shows the position of the trailing edge of the blob in the dynamical phase. The speed measured in the dynamical phase matches well with the average speed of  $230 \text{ km s}^{-1}$  as derived crudely by analysing TRACE image sequence. We note that the plasma column was built well before the flare event, while the dynamical phase of the blob was achieved just before the rising phase of the flare. The rising speed of the plasma column before the detachment of the blob is  $\approx 126 \text{ km s}^{-1}$  before the occurrence of the flare event. This phase of the rising of the plasma column is clearly evident in Figure 2 during 05:24–05:28 UT. The denser and brighter material also filled in the plasma column during this time span, which later detached in the form of the observed plasma blob.



The average sound speed at the formation temperature of Fe XI 171 Å ( $T_f = 1 \times 10^6$  K) is  $\approx 150 \text{ km s}^{-1}$ . Therefore, the blob rose in a plasma column with a rather low subsonic speed in its initiation phase. However, it accelerated in the dynamical detachment phase to a speed of  $215 \text{ km s}^{-1}$ . Therefore, the blob propagated at a supersonic speed, quickly changed its shape, and finally became fainter against the background by most likely dissipating its energy and material draining back to the low atmosphere (see the movie trace-eruptions.avi in Online Supplementary Material). It should be noted that the whole process had two phases: first the initiation phase in which the plasma column and associated cylindrical plasma blob were build-up, followed by the second dynamical stage when the plasma blob became detached and moved up in the corona at a supersonic speed within a few minute time scale. The projected speed that is quoted here is in the dynamical phase and is consistent both with H $\alpha$  and TRACE observations.

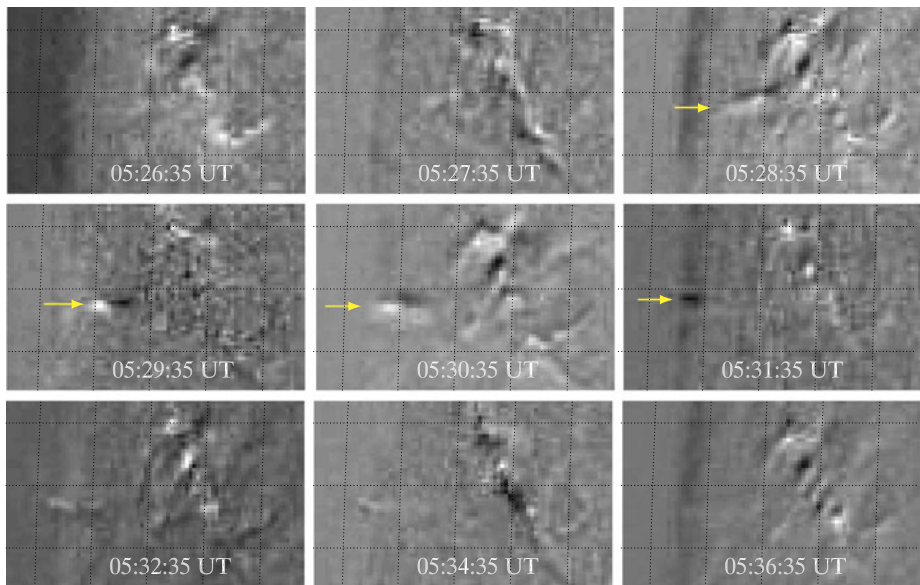
## 2.2. H $\alpha$ Observations

The H $\alpha$  observations of this active region was carried out at Culgoora Solar Observatory at Narrabri, Australia by using a 12 cm  $f/15$  Razdow solar patrol telescope equipped with an H $\alpha$  filter of the Lyot type that has a pass-band width of  $0.5 \text{ \AA}$ . The raw images were recorded by an 8 bit,  $1024 \times 1024$  pixel CCD camera system with a pixel size of  $6.7 \text{ \mu m}$ . The spatial resolution of the camera is  $2''$  per pixel. The typical cadence for the present observations is at least 1 frame per minute. The observations were carried out with a field of view of the full solar disk. Figure 4 shows a sequence of images of the propagating blob emphasised by yellow arrows from AR10808 before the M-class flare during 05:26 UT–05:36 UT. The difference images of Figure 4 are a  $160'' \times 100''$  partial field of view provided to us by Culgoora Solar Observatory under its data use policy. Although the resolution of the images is not very high, it should be noted that this is the only H $\alpha$  observations that are available from the ground as this unique event occurred in its day-light time zone. These H $\alpha$  time series are thus very useful and show the unique signature of the propagation of a *low-temperature* counterpart of the plasma blob observed by TRACE propagating away from the flare site towards the eastern limb in a projection. A careful investigation of the H $\alpha$  image sequence shows that the blob was initially of a cylindrical shape of the length of  $\approx 22 \text{ Mm}$  and width of  $\approx 5 \text{ Mm}$ . The length and width are found to be consistent with the observed TRACE images in the dynamical phase of the blob. Therefore, we conclude that initially the length to width ratio is 4.4. It should also be noted that not only the position but also the length to width ratio may be influenced by projection effects. The blob changed its shape quickly and faded within 4–5 min of its evolution as visible in H $\alpha$  at 05:28 UT. The measured lower-bound speed of this propagating blob is found to be  $\approx 200 \text{ km s}^{-1}$ . This is again the projected speed of the blob, and the actual speed may be higher compared to this lower-bound estimated speed. The average sound speed of the H $\alpha$  formation temperature ( $T_f = 1 \times 10^4$  K) is  $15 \text{ km s}^{-1}$ . Therefore, the blob propagated at a supersonic speed.

## 3. Theoretical Modelling and Interpretation

### 3.1. Survey of Possible Interpretations

As we have explained in the previous section, the analyses of the H $\alpha$  and TRACE 171 Å data between 05:24 UT–05:36 UT well before the M6.2-class flare from AR10808 on 9 September 2005 show the observational evidence of the supersonic plasma blob that propagated in the higher solar atmosphere at a supersonic speed of  $\approx 215 \text{ km s}^{-1}$ .



**Figure 4** Selected H $\alpha$  difference images obtained from observations at Culgoora Solar Observatory showing a moving blob structure towards the eastern limb highlighted by yellow arrows. The size of each image is  $160'' \times 100''$ .

We firstly explore the possibility of interpreting this supersonic blob as a reconnection-generated plasmoid. The observed blob may be the plasmoid as recorded previously by Manoharan and Kundu (2003) due to magnetic reconnection during the rising phase of an M-class flare. They have observed the motion of plasma blobs associated with a sigmoid, Moreton wave, CME injection in the interplanetary space, and associated radio bursts from AR9393 on 2 April 2001 at 11:00 UT. They have also found magnetic reconnection around a coronal null point as a cause of such eruptions and associated phenomena. Recently, multiple plasmoids and their dynamics have also been observed in solar flares (Bárta, Karlický, and Žemlička, 2008; Nishizuka *et al.*, 2010). However, such plasmoids are the high-speed plasma blobs that are accelerated outwards from the reconnection point in the solar atmosphere and usually are associated with the rising phase of the solar flares. These plasmoids are often released with CME ejections, supersonic down-flows associated with the HXR emissions, and radio bursts (Manoharan and Kundu, 2003). In the present case, the supersonic blob was observed well *before* the M6.2-class flare, and there is no observational evidence of associated CMEs and radio bursts even in this most violent super-active region associated with this flare on 9 September 2009. Kundu *et al.* (2001) have reported that the plasmoid ejecta are associated with metric/decimetric radio emission that starts significantly after the impulsive hard X-ray (20 keV) and microwave bursts. In this event, however, we did not observe any metric/decimetric or microwave radio emissions as evident in the Culgoora and Learmonth radio spectra, and no impulsive hard X-ray emissions were evident at that time as per RHESSI X-ray flux profiles. These observed facts possibly exclude the formation and acceleration of a supersonic plasmoid in our case. In conclusion, although the morphology of the observed blob and its dynamics are not favourable for the plasmoid ejection, sometimes it may be difficult to distinguish between the plasma blob formed by the reconnection rate change and real plasmoids (Bárta *et al.*, 2007). The detailed analyses



of the magnetic field topology can only differentiate between these two. Moreover, a single plasmoid does not need to be accompanied with radio/HXR emissions always. The most likely interaction of multiple plasmoids may be responsible for particle acceleration and related emissions.

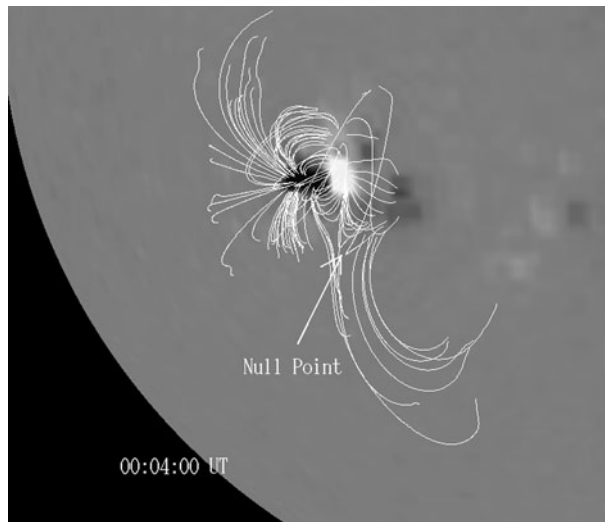
The observed plasma blob may be a reconnection-generated jet as per its typical length, time, and velocity scales of the coronal jets (Nisticò *et al.*, 2009). However, we suggest that the observational evidence points towards the form of a pulse driven blob, which may be a special type of detached jet rather than a classical jet-like structure. Secondly, the blob was visible both in H $\alpha$  and TRACE 171 Å with similar shape and dynamics, which indicate that it was formed by a *multi-temperature* plasma. The bi-directional EUV jets (Innes *et al.*, 1997) are the natural consequences of the flow induced by coronal X-type reconnection as theorised by many workers (Petschek, 1964; Roussev *et al.*, 2001). However, various types of the classical EUV jet as well as such a type of observed plasma packets as move radially outwards from the lower solar atmosphere can either be a direct consequence of the low-atmospheric reconnection of the low-lying loop systems (Nisticò *et al.*, 2009) or the energy build-up due to some magnetic instabilities (Patsourakos *et al.*, 2008). Therefore, the observed blob may also be a consequence of the low-atmospheric reconnection as also is evident in the observations.

If the supersonic blob is not a typical form of the ejecta of flaring active regions, *e.g.*, reconnection-generated classical jets, plasmoids, *etc.*, then the question arises about its identification and the most probable drivers during its initiation and dynamical phases. Recently Zaqarashvili, Kukhianidze, and Khodachenko (2010) have reported the propagation of sausage solitons in the quiet Sun chromosphere using *Hinode*/SOT observations. They have reported the propagation of a supersonic plasma blob in the solar chromosphere, which retained an almost constant shape (length to width ratio) and obeyed the soliton solution. The propagating blob reported in this paper here also moved at a supersonic speed, but changed its relative intensity amplitude as well as the shape (length to width ratio) within 3 min of its launch at 05:27 UT and, then, quickly vanished against the background plasma. Therefore, the soliton description is not the most evident and plausible explanation associated with the observations reported here.

The interpretation of a kink pulse/wave may be another possibility to drive such observed plasma blob/jet in its dynamical phase (Kukhianidze, Zaqarashvili, and Khutsishvili, 2006; Cirtain *et al.*, 2007). However, the axial transversal displacements or a curved form of the pulse was not evident in the observations. The density (and thus intensity) enhancement in the associated inclined flux tube was also not evident as reported by Cooper, Nakariakov, and Williams (2003). Therefore, the possibility of the kink pulse as a driver of the supersonic blob in its dynamical phase is also out of scope under the baseline of the observations. Another possibility, perhaps the most plausible, is then the excitation of a fast MHD pulses/wave train in the flaring active region as a manifestation of the supersonic blob in its dynamical phase. The blob propagated at a supersonic speed and vanished quickly in the corona within 3–4 min. The blob may have been energised by the fast wave train generated in the solar atmosphere (Nakariakov *et al.*, 2004). In such a case, we should observe the quasi-periodic multiple rise and fall of the blob material, which is indeed not evident in the observations presented in the paper. Therefore, the fast MHD pulse train is an unlikely driver for the observed supersonic plasma blob made up by the multi-temperature plasma. In conclusion, the observed blob is neither some classical phenomenon of the solar atmosphere (*e.g.*, Y-shaped typical jet, plasmoid, up-flow, *etc.*), nor it is the signature of less known MHD phenomena (*e.g.*, sausage solitons, fast MHD wave trains, kink pulses, *etc.*).

Therefore, we suggest that the reconnection-generated velocity pulse at the flaring site may be the most likely driver of the plasma blob. The energy release at the reconnection site

**Figure 5** Magnetic field lines by the potential-field source-surface (PFSS) extrapolation, overplotted on the MDI map of 00:04 UT at 9 September 2005, showing a dome-like arrangement of the field lines and the position of the magnetic null point.



in the lower solar atmosphere perturbs the plasma velocity and most possibly creates a velocity pulse that triggers the plasma eruption in the form of a supersonic blob. To the best of our knowledge, this is the first observational signature of the excitation of a velocity-pulse-driven supersonic plasma blob in the solar atmosphere above an active region in the vicinity of a flare site. The most likely possibility is that the low-lying magnetic loops reconnect with each other. This reconnection is at its beginning in the steady state and most probably has a single dissipation region. Since this reconnection region has so far not reached its dynamical state with many plasmoids created, only a small number of particles are accelerated and we do not observe either radio or HXR emission. Hence, this steady reconnection only leads to the rise of the plasma jet which we observed from the very beginning (*e.g.*, Figure 2, 5:24 UT snapshot). The formation of the plasma jet during the steady state reconnection further changes into the detached blob propagating in the corona. As the reconnection rate and reconnection regime change, a velocity pulse may be generated to accelerate the plasma blob. Due to the mass conservation, a density blob is formed in the outflow jet, which detaches from the reconnecting loops and propagates upwards until it vanishes in the solar corona.

We also explore the details of magnetic field topology to understand the most probable generation of such plasma dynamics that we have observed. The magnetic field configuration and topological distribution of its positive and negative polarities are shown in Figure 1. It is clear from Figure 1 that the positive polarity region is stretched towards west with a remote tongue, while the negative polarity is stretched towards east with a remote tongue in the opposite direction as an indicator of the emergence of the twisted magnetic fluxes (*e.g.*, Archontis and Hood, 2010; Li *et al.*, 2007). The potential-field source-surface (PFSS) extrapolation (Figure 5) based on the SoHO/MDI data at 00:04 UT on 9 September 2005 also reveals the formation of a coronal null point above the positive polarity sunspot. This is a very premature configuration of the AR magnetic field well before the event, and a later phase was also associated with high flux-emergence and build-up of the complexity in the region (*cf.*, Figure 1, right panel). Nevertheless, this configuration might force the steady state magnetic reconnection in the lower part of the atmosphere.

The PFSS field lines show that the central positive polarity spot is connected to the two opposite polarity regions on both sides. The field topology in Figure 5 follows the standard

magnetic topology of a 3D reconnection process *via* a separator dome (see Figure 10.27 of Aschwanden (2004) and Fletcher *et al.* (2011a)). In a dome-like fan surface, the symmetry axis is known as the spine containing a null point at the intersection with the fan dome (Aschwanden, 2004). Our observations (Figure 5) show clear evidence of the formation of the fan dome, null-point, and spine at the flare site in the active region. However, the energy release may take place well below this magnetic null point due to flux emergence and the subsequent reconnection process with the existing field lines in the lower solar atmosphere.

The standard scenario of the 3D reconnection predicts re-arrangements of the field lines and mass motion along open field lines in the vicinity of the null point. However, it seems that the steady state reconnection generates the plasma jet in the lower solar atmosphere. There may be some small energy release also during the magnetic field rearrangements of the dynamical reconnection process, but there is no bulk heating of the plasma before achieving the flare maximum. Moreover, there is no expansion or diffusion of the detached plasma along the field lines outward. Therefore, we discard the acceleration of the blob due to the generation of a thermal pulse by bulk heating. This magnetic field re-arrangement during the reconnection process is found to be the driver of a velocity pulse along the radial direction outward and the observed driven supersonic plasma blob. This type of reconnection scenario drives the plasma outward in the radial direction along the spine field lines due to the low-atmospheric reconnection between the low-lying loop systems. This reconnection generates a velocity pulse, which accompanies a shock that steepens in the corona to drive the plasma blob. Therefore, we have the consistent observation of a uni-directional detached jet or plasma blob propagating outwards. Recently, the reconnection-generated velocity-pulse-driven jet (Srivastava and Murawski, 2011) and macro-spicules (Murawski, Srivastava, and Zaqarashvili, 2011) have already been modelled. However, this is the first attempt to numerically model the reconnection-generated and velocity-pulse-driven plasma blob in the solar corona.

Here, the most generic and real situation is that the plasma blob is launched due to an initial radial velocity pulse along the magnetic field lines at the triggering site of the blob. The blob is generated approximately 5–6 Mm above the photosphere with the start of the reconnection process. The reconnection at this height in the low-lying quadrupolar loop system may generate the velocity pulse which may cause the formation of the supersonic plasma blob propagating up in the corona. In the next section, we model numerically the propagation of the supersonic plasma blob generated by a velocity pulse at the reconnection site.

### 3.2. Numerical Simulations

We consider a gravitationally stratified solar atmosphere which is described by the ideal 2D magnetohydrodynamic (MHD) equations:

$$\frac{\partial \varrho}{\partial t} + \nabla \cdot (\varrho \mathbf{V}) = 0, \quad (1)$$

$$\varrho \frac{\partial \mathbf{V}}{\partial t} + \varrho (\mathbf{V} \cdot \nabla) \mathbf{V} = -\nabla p + \frac{1}{\mu} (\nabla \times \mathbf{B}) \times \mathbf{B} + \varrho \mathbf{g}, \quad (2)$$

$$\frac{\partial p}{\partial t} + \nabla \cdot (p \mathbf{V}) = (1 - \gamma) p \nabla \cdot \mathbf{V}, \quad p = \frac{k_B}{m} \varrho T, \quad (3)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}), \quad \nabla \cdot \mathbf{B} = 0. \quad (4)$$

Here  $\rho$  is the mass density,  $\mathbf{V}$  the flow velocity,  $\mathbf{B}$  the magnetic field,  $p$  the kinetic gas pressure,  $T$  temperature,  $\gamma = 5/3$  the adiabatic index,  $\mathbf{g} = (0, -g)$  the gravitational acceleration where  $g = 274 \text{ m s}^{-2}$ ,  $m$  denotes the mean particle mass and  $k_B$  the Boltzmann constant.

We assume that the solar atmosphere is in static equilibrium ( $\mathbf{V}_e = 0$ ) with a force-free magnetic field,  $(\nabla \times \mathbf{B}_e) \times \mathbf{B}_e = 0$ . At this equilibrium the pressure gradient is balanced by the gravity force,  $-\nabla p_e + \rho_e \mathbf{g} = 0$ . Here the subscript ‘e’ corresponds to equilibrium quantities. Using the ideal gas law and the  $y$ -component of hydrostatic pressure balance, we express the equilibrium gas pressure and mass density as

$$p_e(y) = p_0 \exp\left[-\int_{y_r}^y \frac{dy'}{\Lambda(y')}\right], \quad \rho_e(y) = \frac{p_e(y)}{g\Lambda(y)}. \tag{5}$$

Here  $\Lambda(y) = k_B T_e(y)/(mg)$  is the kinetic pressure scale-height, and  $p_0$  denotes the kinetic gas pressure at the reference level that we choose in the solar corona at  $y_r = 10 \text{ Mm}$ . We adopt an equilibrium temperature profile  $T_e(y)$  for the solar atmosphere that is close to the VAL-C atmospheric model of Vernazza, Avrett, and Loeser (1981).

We assume that the initial magnetic field satisfies a current-free condition,  $\nabla \times \mathbf{B}_e = 0$ , and it is specified by the magnetic flux function,  $A$ , such that  $\mathbf{B}_e = \nabla \times (A\hat{\mathbf{z}})$ . We set an arcade magnetic field by choosing

$$A(x, y) = B_0 \Lambda_B \cos(x/\Lambda_B) \exp[-(y - y_r)/\Lambda_B], \tag{6}$$

where  $B_0$  is the magnetic field at  $y = y_r$ , and the magnetic scale-height is  $\Lambda_B = 2L/\pi$ . We use  $L = 30 \text{ Mm}$ .

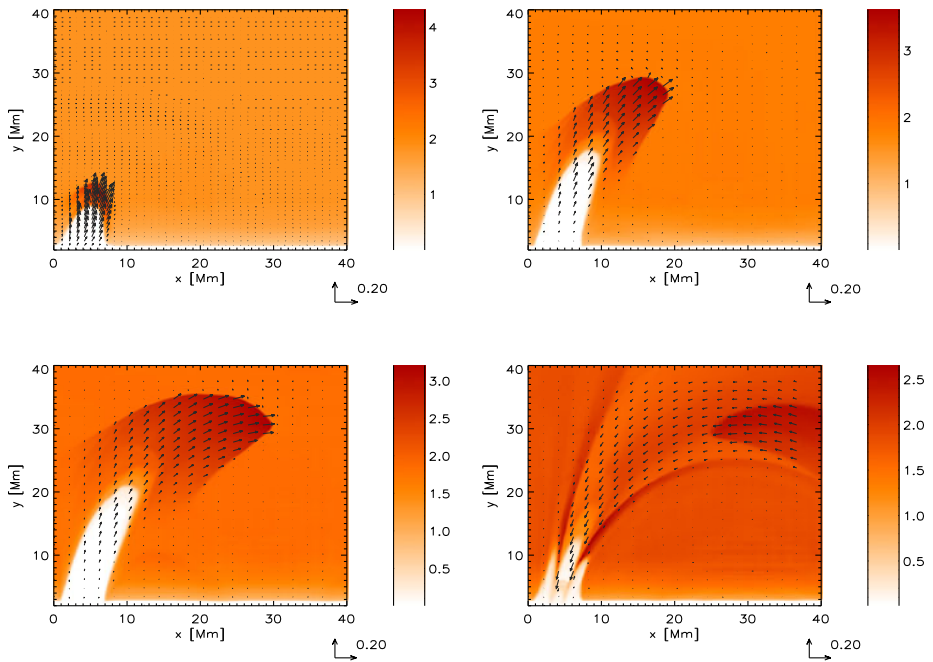
We initially perturb the above equilibrium impulsively by a Gaussian pulse in the vertical component of velocity,  $V_y$ , viz.,

$$V_y(x, y, t = 0) = A_v \exp\left[-\frac{(x - x_0)^2 + (y - y_0)^2}{w_p^2}\right]. \tag{7}$$

Here  $A_v$  is the amplitude of the pulse,  $(x_0, y_0)$  is its initial position and  $w_p$  denotes its width. We choose and hold fixed  $x_0 = 4 \text{ Mm}$ ,  $y_0 = 5 \text{ Mm}$ ,  $w = 2 \text{ Mm}$ , and  $A_v = 300 \text{ km s}^{-1}$ .

Equations (1)–(4) are solved numerically using the code FLASH (Lee and Deane, 2009). This code implements a second-order unsplit Godunov solver with various slope limiters and Riemann solvers, as well as adaptive mesh refinement (AMR). We set the simulation box of  $(-2.5, 65) \text{ Mm} \times (2, 45.5) \text{ Mm}$  along the  $x$ - and  $y$ -directions and impose all plasma quantities to be fixed in time at all four boundaries of a simulation region. In all our studies we use AMR grid with a minimum (maximum) level of refinement set to 4 (7), respectively. The refinement strategy is based on controlling numerical errors in temperature. Every block consists of  $8 \times 8$  identical numerical cells.

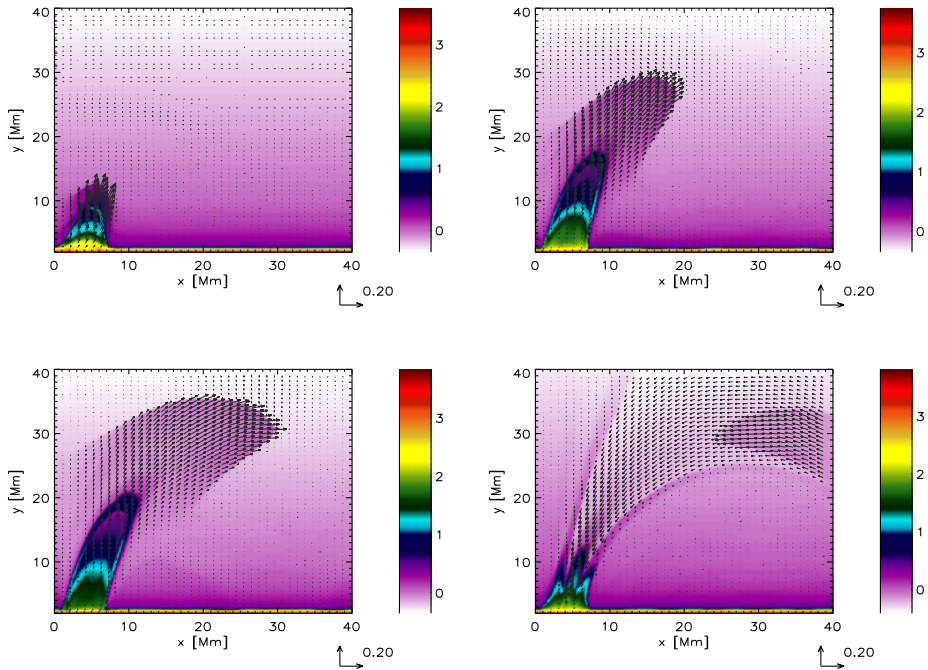
Figure 6 displays the spatial profiles of plasma temperature (colour maps) and velocity (arrows) resulting from the initial velocity pulse which splits into counter-propagating parts. As the plasma is initially pushed upwards the under-pressure results in the region below the initial pulse. This under-pressure sucks up cold photospheric plasma which lags behind the shock front. The pressure gradient force works against gravity and forces the chromospheric material to penetrate the solar corona. At  $t = 25 \text{ s}$  this shock reaches the altitude of  $y \approx 10 \text{ Mm}$ . The next snapshot (top right panel) is drawn for  $t = 100 \text{ s}$ . At this time the shock reached the altitude of  $y \approx 30 \text{ Mm}$  while the cold plasma blob is located at  $y \approx 18 \text{ Mm}$ . By the next moment of time (bottom left panel) the shock has already moved up to the right boundary and the cool counterpart of blob exhibits its developed phase. It is



**Figure 6** Numerical results: Temperature (colour maps) and velocity (arrows) profiles at  $t = 25$  s, 100 s, 150 s, and 600 s (from left-top to right-bottom). Temperature is drawn in units of 1 MK. The arrow below each panel represents the length of the velocity vector, expressed in units of  $200 \text{ km s}^{-1}$ .

also evident in the  $\text{H}\alpha$  and TRACE observations that a cool core of 10 000 K and hot coronal plasma maintained at 1–2 MK temperature are simultaneously present in the plasma blob. The shock-heated supersonic plasma as well as the cool counterpart both disappear in the corona at  $t = 600$  s (bottom right panel). This matches well the observations. The blob already subsided and the plasma began to flow downward, being attracted by gravity. In the present simulation, we only assume the reconnection as a cause that effectively generates the radial velocity pulse. We do not invoke the reconnection-generated joule heating in our model as it can generate the thermal pulse in the ambient medium of certain spatio-temporal scale that can launch the heated plasma upward into the magnetised atmosphere above the reconnection region (Srivastava and Murawski, 2012). Therefore, our model takes the flexibility to not consider any initial conditions generated by reconnection, and we initiate this process with the launch of the radial velocity pulse triggered due to reconnection process. We do not invoke therefore either the heating or the losses due to thermal conductivity and radiation in our model. The inclusion of these factors will be the subject of our future study.

Figure 7 displays the spatial profiles of the plasma density (colour maps) and velocity (arrows) resulting from the initial velocity pulse which splits into counter-propagating parts. In the snapshot (top right panel), drawn for  $t = 100$  s, the shock reached the altitude of  $y \approx 30$  Mm, while the denser cool plasma blob is located at  $y \approx 18$  Mm. By the next moment of time (bottom left panel) the shock has already moved up to the right boundary and the cool counterpart of blob exhibits its developed phase. It is also evident in the  $\text{H}\alpha$  and TRACE observations that a cool and denser core of 10 000 K and comparatively less dense hot coronal plasma maintained at 1–2 MK temperature are simultaneously present in the plasma blob. These findings of the numerical simulation validate our multi-wavelength



**Figure 7** Numerical results: Density (colour maps) and velocity (arrows) profiles at  $t = 25$  s, 100 s, 150 s, and 600 s (from left-top to right-bottom). Density is drawn in logarithmic density scales. The arrow below each panel represents length of the velocity vector, expressed in units of  $200 \text{ km s}^{-1}$ .

observations of detached, blob-shaped jet up to some extent. The shock-heated supersonic plasma as well as cool counterpart both disappear in the corona at  $t = 600$  s (bottom right panel), which matches well with the observations. The blob already subsided and the plasma began to flow downward, being attracted by gravity. However, the clear-cut detachment of the blob material from its origin point is not as clearly visible as in the observations.

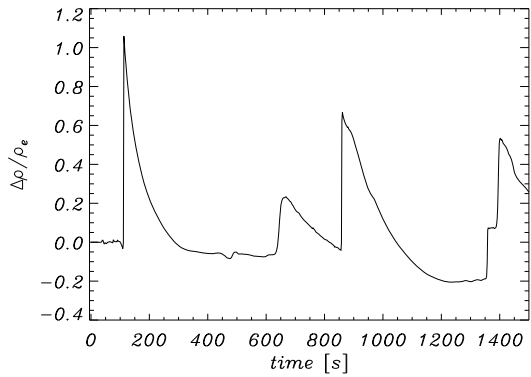
Figure 8 illustrates the relative mass density  $(\rho - \rho_e)/\rho_e$  that is collected in time at the detection point ( $x = 20$ ,  $y = 30$ ) Mm for the case of Figure 7, which mimics the observed blob-shaped detached jet. As a result the mass falls off with height and upwardly propagating waves steepen rapidly into shocks. The arrival of the first shock front to the detection point is at  $t \approx 115$  s. The second shock front reaches the detection point at  $t \approx 865$  s, *i.e.*, after  $\approx 750$  s. This secondary shock results from the reflected wave from the transition region. Therefore, the observation of the intensity (thus density) variations in the detached phase of the blob, as evident in  $\text{H}\alpha$  and TRACE, is due to the variation of density in the plasma blob by the periodic steepening of velocity pulses.

#### 4. Discussion and Conclusions

Using multi-wavelength observations from TRACE 171 Å SoHO/MDI, and  $\text{H}\alpha$  from Culgoora Solar Observatory, we observed a supersonic plasma blob just before the M6.2-class flare in AR 10808 on 9 September 2005. The blob moved at a supersonic speed of  $\approx 215 \text{ km s}^{-1}$  in its dynamical phase and quickly vanished in the corona. The supersonic



**Figure 8** Time profile of perturbed mass density collected at  $(x = 20, y = 30)$  Mm for the case of Figure 7. Time  $t$  is expressed in units of 1 s.



speed, vanishing nature, and increase in the intensity (thus density) followed by its decrease during the life-time of the blob all collectively support the excitation of a velocity pulse just in the vicinity of the magnetic null point and reconnection is suggested to be a primary driver. At the same place, the repetitive plasma dynamics at 05:15 UT and 05:50 UT have also been observed. However, they were much fainter and the blob-shaped plasma eruption was not evident in those processes. Moreover, those eruptions were also not visible in the cool  $H\alpha$  temperature. Therefore, we have a unique observational signature of the propagation of a supersonic plasma blob during the multiple plasma eruptions at the flare site in AR 10808. This is the most likely clue of the occurrence of the repetitive reconnection processes in the observed active region well before and close to the M-class flare, which generated the multiple plasma eruptions as well as the supersonic blob, which may also be a detached jet that moved along the spine field lines above the null point.

The velocity pulses launched by the photosphere motions and granular convection power can launch the spicule-like small-scale plasma jets in the lower solar atmosphere (Murawski and Zaqarashvili, 2010; Malins and Erdélyi, 2007). However, in the active regions, the reconnection event and large energy deposition can generate the strong velocity pulses that launch such type of pulse-driven observed plasma blobs. Therefore, the reconnection-generated velocity pulse is found to be an efficient driver of the supersonic plasma blob. The energy release by a recurrent 3D reconnection process *via* the separator dome below the magnetic null point, between the emerging flux and pre-existing field lines in the lower solar atmosphere, is found to be the driver of a radial velocity pulse outwards that accelerates this plasma blob in the solar atmosphere. The observed magnetic field and its extrapolation at the flare site mimic the formation of a 3D null point and the reconnection through the separator dome that are well established in theory (Aschwanden, 2004). Our numerical modelling shows the formation of a supersonic plasma blob with a speed of  $\approx 215 \text{ km s}^{-1}$ , which is triggered due to the generation of a Gaussian velocity pulse at a height of 5 Mm from the photosphere where the low-lying quadrupolar loop system probably reconnects (*cf.*, Figures 1, 2, and 5). The pulse steepens into shock with the evolution of temperature gradient, the low pressure behind it causing the uplift of cool low-atmospheric plasma in the corona. The observation of multi-temperature plasma in the blob matches well with this evolution of the multi-temperature plasma in various parts of the simulated plasma blob, *i.e.*, the cool confined material enveloped by a heated plasma. The observed supersonic blob powered by reconnection-generated velocity pulse may be very significant in fulfilling the coronal energy losses above an active region, if they occur repeatedly in the corona. This is the unique observational evidence of such high-speed energy packets which may occur under the particular magnetic field configuration in the flaring regions. If we assume the typical coronal

electron density above active region loop-like field configuration to be  $n_e = 1.0 \times 10^{10} \text{ cm}^{-3}$ , the phase speed  $V_{\text{ph}} = 215 \text{ km s}^{-1}$ , and the non-thermal speed in the form of unresolved mass motions in the coronal plasma as  $V_{\text{nt}} = 40 \text{ km s}^{-1}$ , then such MHD pulse-driven blobs may carry an energy flux of  $E_f = 7.0 \times 10^6 \text{ erg cm}^{-2} \text{ s}^{-1}$  to submit to the corona, if their origin is non-thermal as in this case. This energy transport may be very sufficient to contribute to balance the coronal losses above active regions.

In conclusion, these first observations provide important clues about the plasma dynamics driven by a velocity pulse, and its role in energy transport in the solar atmosphere. The rare multiwavelength observations of the blob propagation in the solar corona also have provided the clues of a steady reconnection process in the low atmosphere well before the flaring event. Further multi-wavelength observational studies will be required to shed more light on the transport of mass and energy by such reconnection-generated and pulse-driven-plasma eruptions.

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