Geometry and dynamics of cool UV flare loops observed by *IRIS*

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ABSTRACT

We present analysis of IRIS ultraviolet observations of cool loops visible after the maximum of M6.5 solar flare on June 22, 2015. The detailed investigation of the physical parameters and models of these loops was presented in Mikuła et al. (2017). The line profiles were modeled using Cloud Model and this allowed us obtaining the reliable physical parameters characterizing the moving plasma inside loops, e.g. velocity along the line-of-sight. Here we present the next step of the work – the reconstruction of the shape of the analyzed flare loops. The geometric method, that allows us to reconstruct the true shape of loops was introduced by Loughhead, Wang & Blows (1983). Based on two-dimensional images of a given structure located on the solar disk or at the solar limb, we can obtain their true orientation and size. The shape of the analyzed loops was determined mainly from images obtained by IRIS, supplemented with SDO/AIA 171 A data in some cases. Using basic geometry and some assumptions we reconstructed geometrical parameters of the loop system and we could present them in three-dimensional space. Thanks to simple calculations based on method presented in Loughhead and Bray (1984) we could also get so-called true velocity of downflow/upflow of plasma, i.e. velocity along the axis of the loops. The obtained results for each loops were compared with the corresponding free–fall velocities on the Sun.

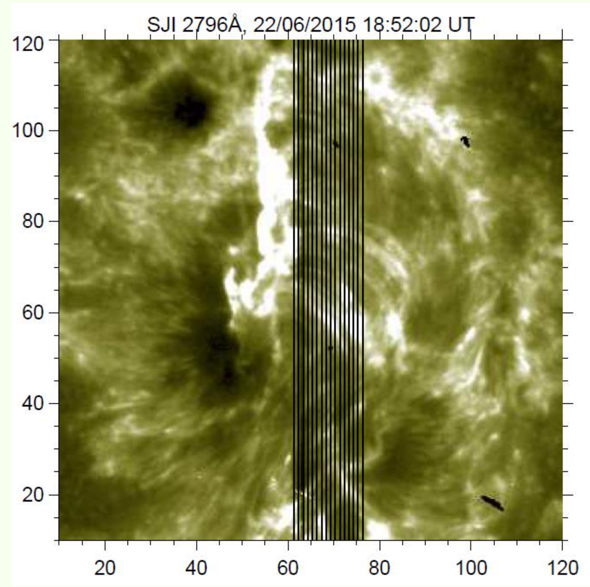
OVERVIEW OF THE FLARE OBSERVATIONS

We analysed solar flare observed on June 22, 2015. The flare has been observed by *IRIS* in near-UV (NUV) and far-UV (FUV) ranges and shows flare loops systems during its gradual phase.

Solar flare on 2015 June 22

M6.5 class flare
Active region: NOAA 12371
Start time: 17:39 UT
Peak time: 18:23 UT

***IRIS* observations**
Time duration: 17:00 – 21:14 UT
450 rasters / 16 slit positions per raster



1. OBSERVED COOL FLARE LOOPS

We analysed 8 cool flare loops (marked from A to H, see Fig. 1) in field-of-view of IRIS. The loops were selected in differents moments when they were clearly visible in IRIS SJ images in 1330, 1400 and 2796 Å. The system of the loops were observed during the whole gradual phase of the flare.

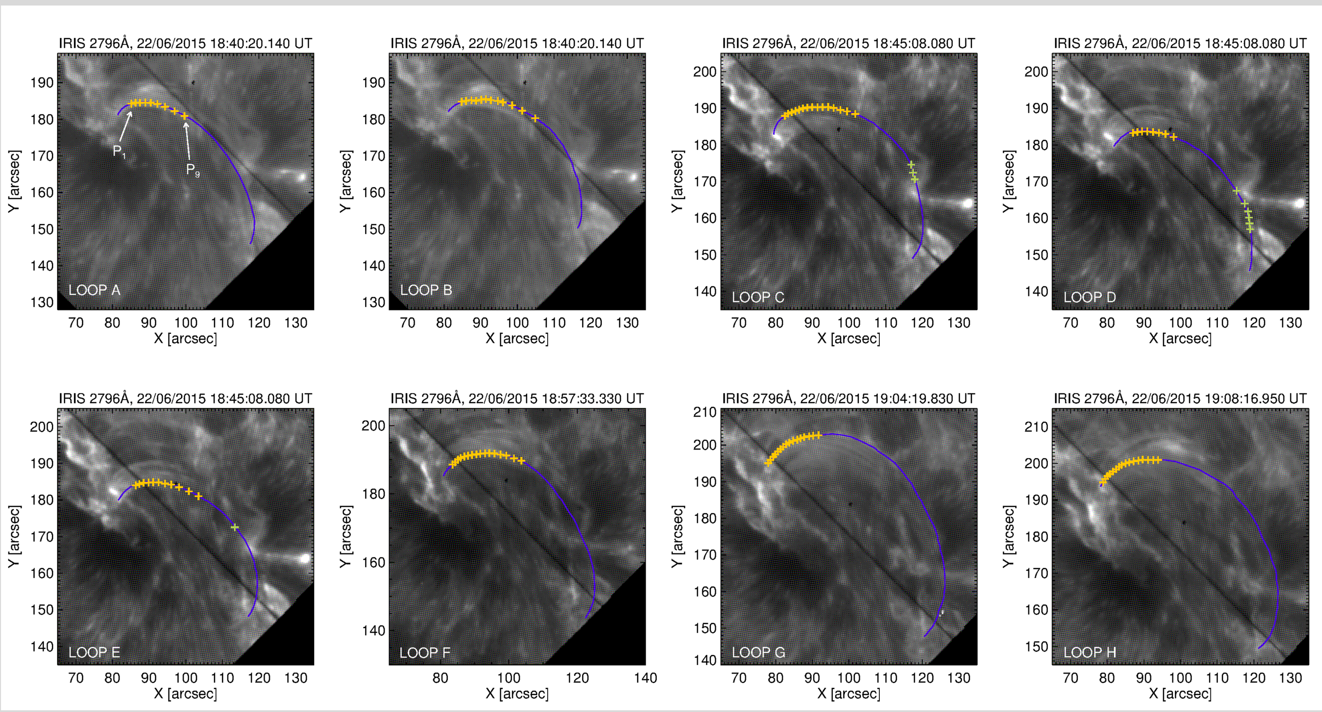


Figure 1. The selected loops visible in SJIs 2796 Å (roll angle -45°). The central axis of every loop is marked by solid blue liine. The intersections of the central axis of the loop and slit of the IRIS spectrograph which we determined e.g. the line-of-sight velocity from Mg II h line profiles by using the cloud model method (see Mikuła et al. 2017) are marked with yellow and green crosses. The colors are different to distinguish the parts of the loops on both sides of their top. The black field in the IRIS SJIs means limited FOV of the telescope.

2. GEOMETRY OF THE COOL FLARE LOOPS – THE RECONSTRUCTION METHOD

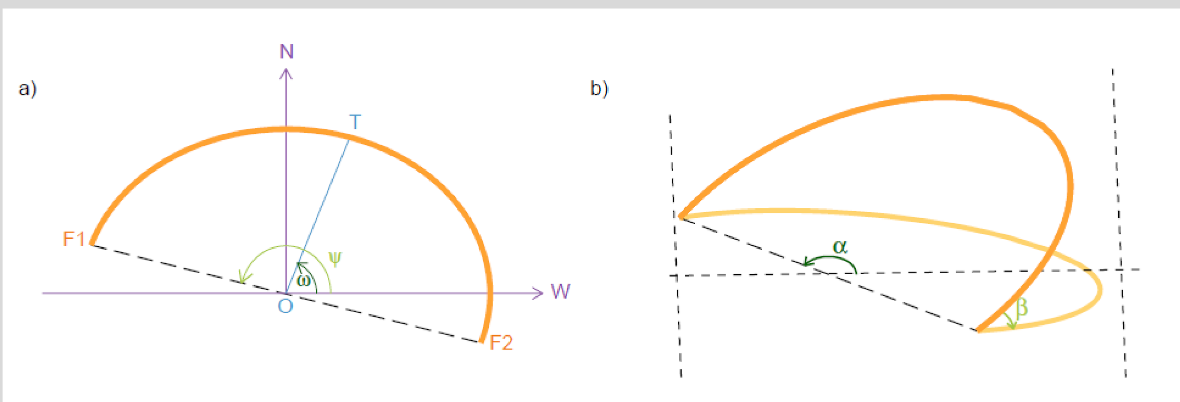


Figure 2. The scheme shows the theoretical, symmetrical loop projected on the solar disk and values of (ψ , ω) angles (a), and orientation of the loop described by (α, β) angles (b).

To reconstruct the true shape from 2D images of every selected loop we used the method introduced by Loughhead, Wang & Blows (1983). The method has three simple assumptions:

1. The central axis of the loop is lying in its plane,
2. The footpoints of the loop are identified on the solar disk,
3. The loop is symmetrical in its plane about its central axis.

The method used two observable angles: ψ and ω (see Fig. 2a). Measuring these two angles and knowing the position of the loop on the solar disk (φ, λ) and the solar pole (P_O, B_O) allowed us to determine azimuthal α and inclination β angles. These angles described the orientation of the loop on the solar disk (see Fig. 2b).

3. THE TRUE SHAPE OF THE COOL UV FLARE LOOPS

Here, we present an example of one of the loop and how the method works in practice (Fig. 3), and the results obtained from the reconstruction of the true shapes of loops (Fig. 4). The detailed information, i.e. true sizes of the loops, shapes, position on the solar surface and inclination to the solar disk were obtained for the first time from the UV observations. The obtained results show that the system of the loops visible during the gradual phase consisted of relatively quiet loops significantly inclined to the solar surface.

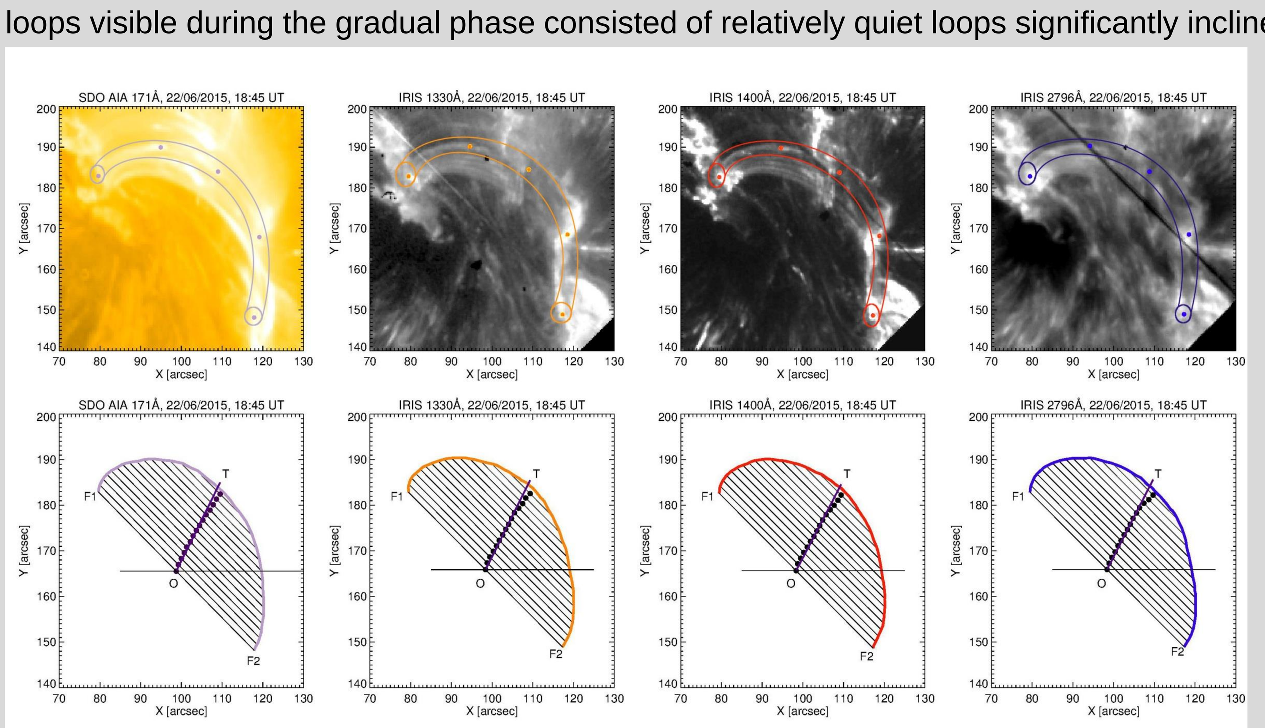


Figure 3. Examples of the loops at 18:45 UT (the loop C). The upper panel shows the selected structure in SDO/AIA 171 Å, and IRIS SJIs 1330, 1400 and 2796 Å images. The central axis of the loops is marked with dots (i.e. the footpoints of the loop), and the whole structure is outlined by contour. The lower panel shows the central axis of the loop from every map. For the loop we made the symmetry test – we set the parallel lines to the lines joining the footpoints |F1F2| (black solid lines). The middle of the lines is marked with dots. Based on this, we determined the |OT| section by the interpolation (violet solid line). A horizontal line crossing point O indicates the E-W direction.

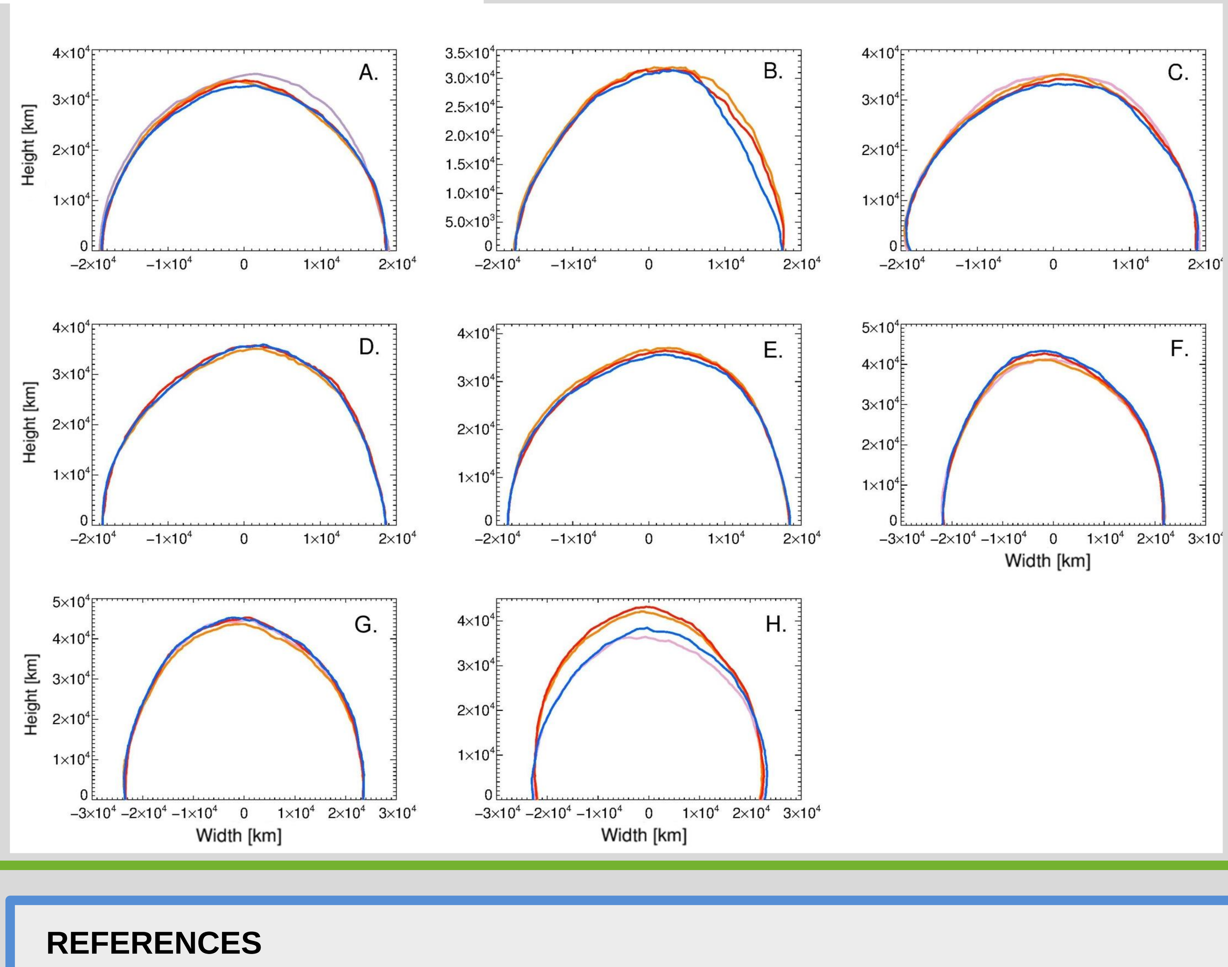
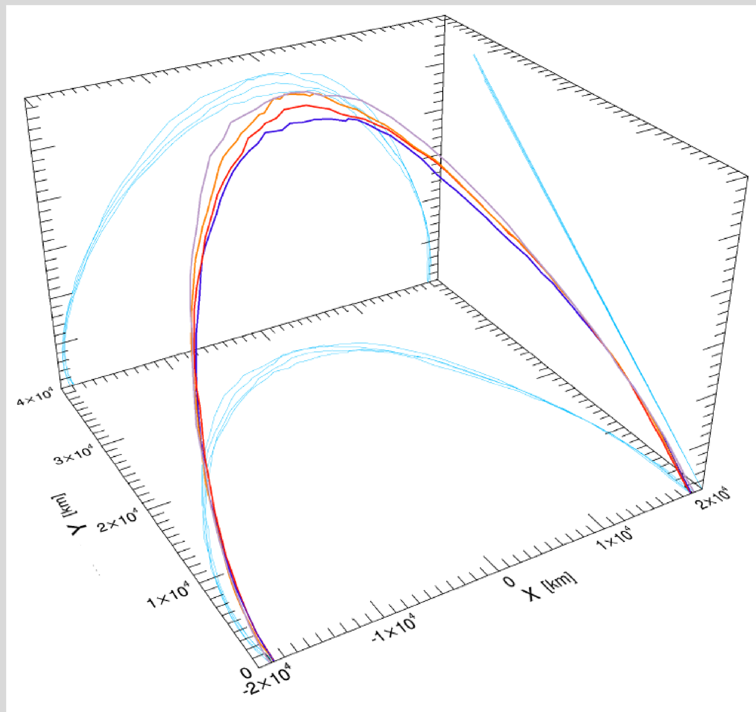


Figure 4. The true shape of the every selected cool flare loop obtained from the reconstruction method. The colors of the loop corresponds to the colors in the Fig. 3. The average value of azimuthal angle α is 142.3°, and the average inclination β is -34.4°. The geometry has been converted from arcsec to kilometers. One can see that the cool flare loops at the beginning of the gradual phase are not high structures, they extend above 30000 km. The loops get higher with time. The H loop measures nearly 45000 km. At the beginning the distance between the footpoints is ~37000 km. As the flare ribbons moves apart the distance between loops reaches ~47000 km.

4. EXAMPLE OF THE 3D GEOMETRY



By using the simple geometry, we obtained the height h of the loop from the geometry reconstruction method and using the formula:

$$h_A = h\cos\beta$$

we calculated the height of the top of the loop above the solar disk h_A. In this way, we could determine the 3D geometry for all 8 loops (see one example in Fig. 5.)

Figure 5. Example of the 3D geometry of the loop (the C loop). The structure is reconstructed in four UV channels: SDO/AIA 171 Å (violet line) and IRIS SJI – 1330 Å (orange line), 1400 Å (red line) and 2796 Å (dark blue line). The light blue solid lines are projections of the loop on the XY, XZ and YZ planes.

5. PLASMA FLOWS – RESULTS

By using the other method introduced by Loughhead & Bray (1984) we calcuclated the true plasma flows. The method use the values of the line-of-sight velocity obtained from e.g. the Cloud Model method, and the results from the reconstruction procedure. They defined formula to calculate the true plasma flows along the analysed structures, The Doppler velocity v is given by a following formula:

$$v = nV_0$$

where V_0 is the true plasma velocity in the point (x, y, 0) (see figure 1), and n is a directional cosine to the line-of-sight. The Fig. 6 and 7 shows the results of obtained plasma velocity flows along the central axis of the cool UV flare loops, and their comparison with the free fall velocity on the solar surface.

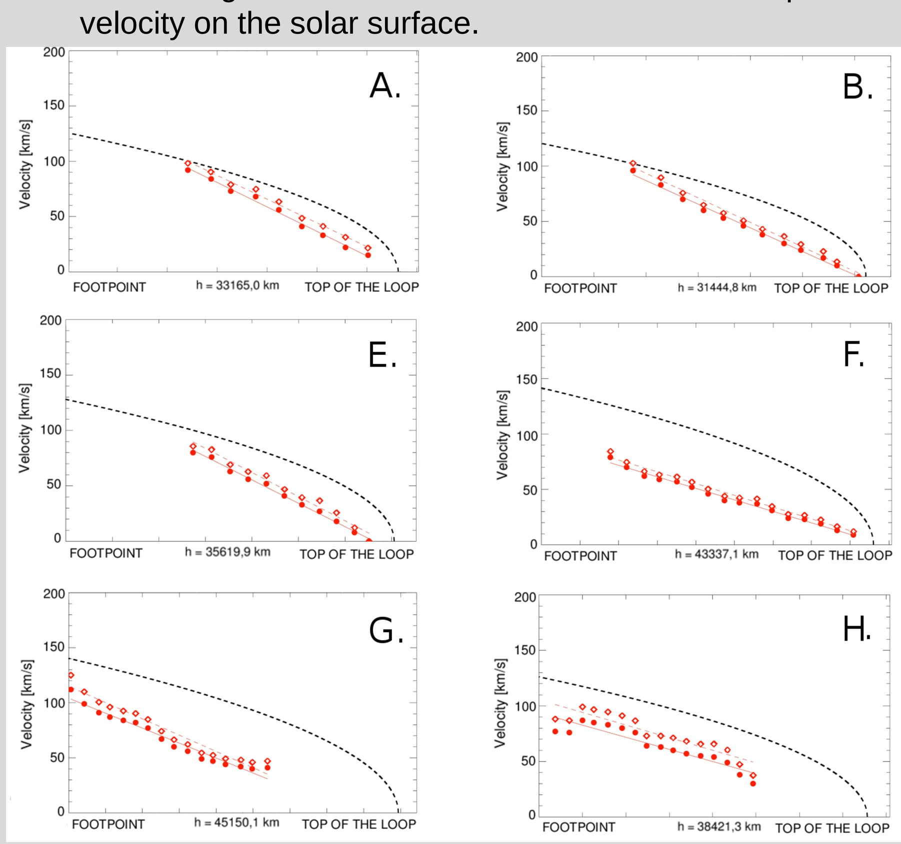


Figure 6. The comparison of the true plasma flows along the loops A, B, E, F, G and H and the computed free fall velocity along the loop. The black dotted line means the free fall velocity. The red dots shows Doppler velocities obtained from the Cloud Model, and the red diamonds shows the true plasma velocity flows along the loop. The points correspond to points showed in Fig. 1. The P_1 point from Fig. 1 is the closest point of the footpoint. The true plasma and the free fall velocities were calculated for h_A. The true plasma velocities are lower than the free fall velocity. It's the reasonable result reported also in previous papers and this retardation can be caused by different mechanisms, e.g. complicated, spiral structure of the magnetic field inside the loops or the resistance caused by plasma already presented in the loops, which partially blocks the downflow.

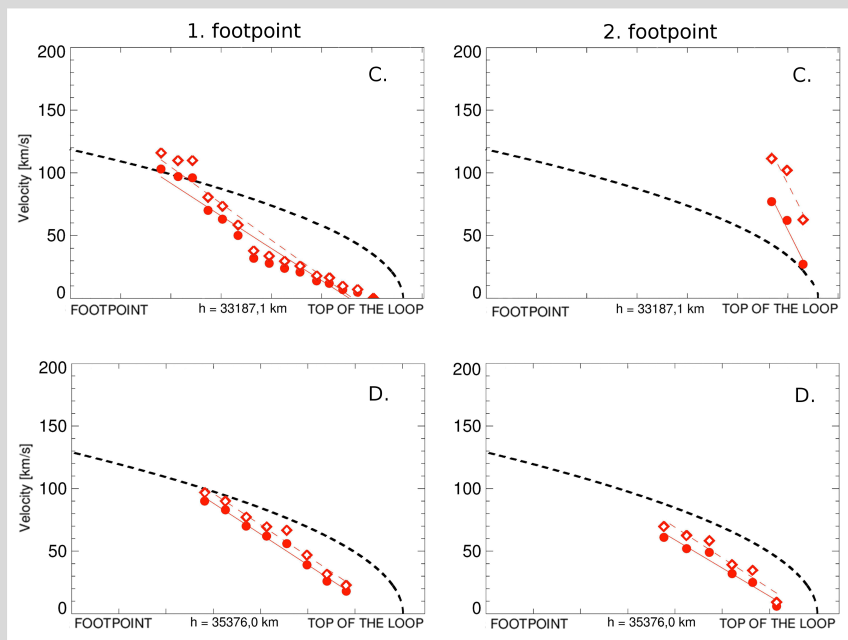


Figure 7. Comparison of the true plasma flows along the two legs of the loops C and D and the free fall velocity along the loop. The signs are the same as in Fig. 6. The true plasma downflow velocities are higher than the free fall velocity in the first leg of loop C in its lower part and in the second leg of the same loop, close to the loop's top. It could be caused if the central axis of the loop is not correctly determined.

6. CONCLUSIONS

- For the first time the 3D geometry of cool flare loops observed in near- and far-UV spectral lines were determined using the special reconstruction procedures.
- The obtained results show that the flare loops of the arcade visible during the gradual phase of the flare are significantly inclined to the surface of the Sun. At the beginning of the gradual phase, the loops selected for analysis are not too high structures, reaching around 30,000 km. Over time, higher and higher loops are observed.
- Using the reconstructed real shapes and orientation of loops, and measured LOS Doppler velocities, we could determined the true downflow velocities of plasma along the axes of loops.
- In most cases the velocity of plasma do not exceed the free-fall velocity computed for given loop. This retardation can be caused e.g. by complicated structure of the magnetic field inside the loops or by plasma already presented in the loops, which partially blocks the downflow.
- The difference between the true velocity of plasma and free-fall velocity decreases in lower parts of loops. This effect can be connected with the specific observing mode of IRIS – we could not follow the motion of the specific plasma blobs along the loop. Instead, we analysed only local flows in different areas of the loops defined by IRIS slit positions.

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