When hot meets cold: post-flare coronal rain

Wenzhi Ruan (wenzhi.ruan@kuleuven.be)
Centre for Mathematical Plasma Astrophysics

Yuhao Zhou
Centre for Mathematical Plasma Astrophysics, KU Leuven

Rony Keppens
Centre for Mathematical Plasma Astrophysics, KU Leuven https://orcid.org/0000-0003-3544-2733

Article

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All solar flares demonstrate a prolonged, hourlong post-flare (or gradual) phase, characterized by arcade-like, post-flare loops (PFLs) visible in many extreme ultraviolet (EUV) passbands. These coronal loops are filled with hot $\sim 30$ MK – and dense plasma, evaporated from the chromosphere during the impulsive phase of the flare, and they very gradually recover to normal coronal density and temperature conditions. During this gradual cooling down to $\sim 1$ MK regimes, much cooler $\sim 0.01$ MK – and denser coronal rain is frequently observed inside PFLs. Understanding PFL dynamics in this long-duration, gradual phase is crucial to the entire corona-chromosphere mass and energy cycle. Here we report the first simulation in which a solar flare evolves from pre-flare, over impulsive phase all the way into its gradual phase, which successfully reproduces post-flare coronal rain. This rain results from catastrophic cooling caused by thermal instability, and we analyse the entire mass and energy budget evolution driving this sudden condensation phenomenon. We find that the runaway cooling and rain formation also induces the appearance of dark post-flare loop systems, as observed in EUV channels. We confirm and augment earlier observational findings, suggesting that thermal conduction and radiative losses alternately dominate the cooling of PFLs. Since reconnection-driven flares occur in many astrophysical settings (stellar flares, accretion disks, galactic winds and jets), our study suggests a new and natural pathway to introduce multi-thermal structuring.

Solar flares represent explosive phenomena in the solar atmosphere, where $10^{28} - 10^{32}$ ergs of energy originally stored in the solar magnetic field can suddenly be released via magnetic reconnection [1, 2]. Reconnection is also considered to be relevant for many other types of flaring behaviours observed throughout the universe [3, 4]. The time development
of a solar flare event can be divided into three phases: a preflare phase, a sudden, impulsive phase and a gradual or post-flare phase [5]. The magnetic energy is released rapidly in the impulsive phase within a typical timescale of (tens of) minutes. A large fraction of this released energy is transported from the tenuous and hot corona downwards to the denser and colder solar chromosphere via thermal conduction and by energetic electrons [6, 7]. This deposition of energy in the chromosphere leads to a sudden heating of the local plasma, and causes upward evaporation of the plasma to form super hot (∼10 MK) and dense (∼1010 cm−3) arcade-like loop systems at coronal heights. The loops return to their usual coronal conditions (∼1 MK, ∼108 – 109 cm−3) in the following, gradual phase, where field-guided thermal conduction and radiative losses generally contribute to the cooling process [8, 9]. These loops, visible in extreme ultraviolet (EUV), but also in Hα images, are usually called post-flare loops (PFLs) [10].

Thanks to dramatically increased spatio-temporal resolutions in observations, this gradual phase of solar flares is now known to show PFLs which spontaneously develop fine-scale coronal rain [11, 12, 13, 14]. In the multi-thermal coronal rain events, cool and dense rain blobs form in-situ in hot corona, to fall to the chromosphere with speeds up to 100 km s−1. Coronal rain is also observed in non-flaring coronal loops, is frequently found in loops of active regions [15, 16, 17, 18, 19, 20, 21], and this type of coronal rain has been studied previously using magnetohydrodynamic (MHD) simulations [22, 23, 24, 25, 26]. It has been generally accepted that these rain blobs are generated in a catastrophic cooling process, essentially caused by thermal instability [27, 28, 29, 30]. In a catastrophic cooling event, local temperatures drop from 1 MK to below 0.1 MK within one minute, while local densities can increase by orders of magnitude [14]. Observations of flare-driven coronal rain demonstrate that this catastrophic cooling can also happen in PFLs, but this has thus far never been modeled. The actual post-flare coronal rain trigger is yet to be identified: recent work showed that it can not be due to electron beams [31]. Another phenomenon thought to have a close relationship with these sudden condensations are the so-called dark post-flare loops (DPFLs), where some PFL loops suddenly vanish from specific EUV passbands, e.g. at 17.1 nm, 30.4 nm and 21.1 nm [32, 33, 34]. In these DPFLs, an EUV loop which was bright for a while suddenly darkens for several minutes, so effectively disappears between the adjacent EUV loops seen at the same height. It has been suggested that the formation of cool and dense coronal rain may contribute to EUV emission and absorption, inducing DPFL formation [33, 34]. However, this suggestion must still be confirmed in an ab-initio model. Besides coronal rains, multi-thermal plasma behaviour is at stake in many setting, e.g. in galactic outflows or in giant molecular clouds in the interstellar medium [35, 36, 37].

Here we perform an MHD simulation of a flare event from its pre-flare phase all the way into the gradual phase. This simulation finally allows us to understand the complex thermodynamic evolutions of PFLs. For the first time in any modeling effort, we (1) reproduce post-flare coronal rain; (2) quantify the chromosphere-corona mass and energy cycles during PFLs; and (3) demonstrate the intricate relationship between condensations...
and the disappearing EUV loops, or DPFLs.

**Post-flare loop formation and evolution**

In solar flare events, arcade-like PFLs form in the impulsive phase due to magnetic reconnection and are filled with hot and dense plasma by evaporation flows from the chromosphere. In our two and a half dimensional (2.5D) simulation, we simulate the cross-sectional view on an extended flaring arcade system, with the assumption that plasma parameters do not vary in the direction across the arcade. The simulation plane runs perpendicular to the (evolving) flare ribbons that mark the PFL footpoints. The hot PFL plasma releases soft X-ray (SXR) photons via thermal bremsstrahlung and EUV photons of specific energies due to electron de-excitation, making the PFLs light up in the SXR waveband and at selected EUV wavelengths. Synthesizing our MHD simulation in this early impulsive phase gives mock observational views shown in Fig. 1. Solar flares are classified as A, B, C, M or X level, according to their peak SXR flux in the 1-8 Å waveband measured near Earth. This peak flux in our simulation is about $4 \times 10^{-7}$ W cm$^{-2}$ when assuming that the loop width in the third direction is 100 Mm (see also Fig. 2e), therefore the simulated flare is a B level flare.

![Figure 1](image1.png)

**Figure 1:** SXR (panel a, emission in 3-6 keV) and EUV image (panel b, at 13.1 nm) of our simulated flare at its impulsive phase ($t = 6$ min). The right, 13.1 nm emission has peak temperatures at $10^{5.6}$ K and $10^{7}$ K. Solid lines are magnetic field lines.

Fig. 2 demonstrates the full evolution in magnetic topology, from pre-flare current sheet to the formation of PFLs at the impulsive phase (Fig. 2b), extended to the entire evolution of the PFLs through the gradual phase (Fig. 2c,d). There is a vertical current sheet separating regions of opposite field directions at the beginning of our simulation (Fig. 2a).
Magnetic reconnection inside this current sheet produces closed magnetic arcades below and a flux rope above a reconnection site in the impulsive phase \( t \lesssim 8 \text{ min} \). A large amount of magnetic energy released by reconnection is conducted to the high density chromosphere and this produces upward evaporation flows. They fill the generated coronal loops with hot plasma \((\sim 10 \text{ MK})\) and increase the plasma number density by one order in the PFLs (Fig. 2b). Thereafter, the flare enters the gradual phase when we have a rapidly decreasing magnetic reconnection speed \( t \gtrsim 8 \text{ min} \). The PFL temperature decreases slowly due to thermal conduction and radiative losses in this gradual phase, but suddenly triggers thermal instability near \( t \approx 35 \text{ min} \). The loop density also decreases in this period, but is still much higher than the external coronal density (Fig. 2c).

Catastrophic cooling driven by thermal instability condenses local plasma in-situ and leads to high density \( (\text{close to } 10^{11} \text{ cm}^{-3}) \) and cold \( (\text{close to } 0.01 \text{ MK}) \) structures in the coronal PFLs (Fig. 2d). Fig. 2e shows how the SXR flux reaches its peak value at the impulsive phase, to then gradually decrease as the loop temperature drops. The temporal evolution of the total coronal rain material \((\text{i.e. } T_e < 0.1 \text{ MK}, N_e > 10^{10} \text{ cm}^{-3} \text{ and } y > 5 \text{ Mm})\) is also illustrated in Fig. 2e. We note that sudden condensations happen in two successive events during the entire simulated period. These are located in different loop systems, with the second rain event appearing at a higher altitude.

Once condensations happen within PFLs, the formed cold and dense plasma structures will likely fall down from coronal heights due to gravity and hence appear as observed coronal rain blobs. This is fully reproduced in our simulation as demonstrated in Fig. 3. Cold plasma is formed at a PFL looptop at the beginning of the runaway condensation (Fig. 3a). Thereafter, the cold structure extends to lower and higher loops, meanwhile sliding down to one side (Fig. 3b,c). This falling cold plasma gets accelerated to a speed of \( \sim 100 \text{ km s}^{-1} \) by gravity before it enters the chromosphere (Fig. 3d-f). Such a speed is close to that found in coronal rain observations. Considering an acceleration timescale of 10 minutes, the average acceleration rate is lower than the acceleration of gravity. A detailed analysis of rain blob acceleration process for non-flaring (or quiescent) coronal rain was given in [22].

Mass and energy cycles during the gradual phase

Here we investigate the mass and energy cycles in our entire 100-minute simulation of the gradual phase and the role of condensations in it. To do so, we track mass and energy budgets into the coronal part \((y > 5 \text{ Mm})\) of a loop section in which the first round of condensation happens. This loop section is always bounded by (a) the evolving magnetic field line with a fixed footpoint at \( x = -25 \text{ Mm} \) at our lower \( y = 0 \) boundary; and by (b) a similarly evolving field line with footpoint at \( x = -15 \text{ Mm} \) (Fig. 4a). As seen in Fig. 3 and Fig. 4a, this region gets emptied during the first round of condensations, as matter collects along the field lines into localized rain blobs. This entire loop system continuously...
Figure 2: (a-d): Plasma number density (background color map) and magnetic field topology (in red) at $t = 0, 6, 29$ and $45$ min. (e): Temporal evolution of the integral SXR flux (black solid line) and of the total coronal rain matter (blue dashed line). The PFLs have an assumed width of 100 Mm in the invariable $z$-direction, to calculate the SXR flux. The times corresponding to the top panels are indicated in panel (e) with vertical dotted red lines.
Figure 3: (a-c): Plasma number density at $t = 36, 43$ and $50$ min. (d-f): Vertical $y$-component of velocity for the coronal cool plasma ($T_e < 0.1$ MK, $N_e > 10^{10}$ cm$^{-3}$ and $y > 5$ Mm). The solid lines are magnetic field lines.

Plasma moves downward as a result of the above reconnection dynamics and the corresponding area of the selected region continuously decreases during the simulation as quantified by the solid line in Fig. 4b. The area-integrated total energy (kinetic, thermal and magnetic combined, dashed line in Fig. 4b), area-integrated mass (solid line in Fig. 4c) and the area-averaged temperature (solid line in Fig. 4d) of this region also continuously decrease before the first condensation ($t \approx 35$ min). Plasma which evaporated upwards into the corona in the previous impulsive phase now leaks back to the chromosphere in this period, seen in the downward mass flux (dashed line) in Fig. 4c. The decrease of temperature leads to a decrease of the atmospheric scale height. However, this downwards leakage of coronal plasma is severely reduced when the condensation happens after $t \gtrsim 35$ min, since the gas pressure in the coronal part of the loop then decreases rapidly. Therefore, we see a drop of the downward mass flux in Fig. 4c near $t \approx 38$ min, when condensations fully formed. Later on, the downward mass flux experiences a sudden increase, exactly when the cool coronal rain material goes through the lower $y = 5$ Mm boundary of the studied region. The area-integrated mass reaches its minimum value when all cool material leaves and enters the chromosphere. Thereafter, plasma from the chromosphere is injected to the loop again, due to the low pressure inside the loop, leading to an upwards mass flux. The total mass then gradually returns to its value before condensation.

The changing coronal energy budget shows a similar tendency with the changing coronal mass cycle. The energy also experiences a decrease in the pre-condensation and during the
Figure 4: (a): Plasma number density at $t = 52$ min. The region bounded by the field lines starting from $(x, y) = (-25 \text{ Mm}, 0)$ and $(x, y) = (-15 \text{ Mm}, 0)$ and the horizontal line $y = 5 \text{ Mm}$ is investigated in panels b-d. (b): Time evolution of the evolving area (black solid line) and that of integrated total energy (red dashed line). (c): Time evolution of integrated mass (black solid line) and of the mass flux across the lower boundaries of this region. (d): Time evolution of average temperature (black solid line), integral radiative losses (red dashed line) and integral conductive losses (red dashed-dotted line). Blue vertical dashed-dotted lines indicate the starting and ending time of the condensation, and the vertical blue dotted line marks the time of panel a.
condensation phase, to then experience an increase after the condensations merged into
the chromosphere due to renewed plasma injection (Fig. 4b). It has been suggested that
thermal conduction determines the PFLs energy loss at the beginning of the gradual phase
of a flare and that subsequently radiative losses will become dominant [38]. Our simulation
shows that this suggestion is correct before and also during the occurring condensations.
The efficiencies of radiative cooling and of thermal conduction to the energy loss in the
selected region are compared in Fig. 4d. The contribution of thermal conduction is greater
than radiative losses for $t \lesssim 25$ min, but conductive losses drop gradually owing to the
declining temperature gradient. At $t \approx 25$ min, the average temperature is about 3 MK,
and the efficiency of radiative losses becomes most prominent. However, conductive losses
become stronger than radiative losses again when the condensations vanished from the
loop system, as collisions between re-injected flows from both footpoints make the loop hot
again and the radiative loss drop for a while due to the decrease of loop density.

**Catastrophic cooling and rain-induced QPP**

The first round of condensation happens near $t \approx 35$ min. The temporal evolutions of in-
stantaneous maximum/minimum temperature/number density in the condensation region
(the same as marked in Fig. 4a) are illustrated in Fig. 5. Triggering of thermal instability
switches the radiative cooling process from linear to nonlinear, and then leads to a cata-
trophic cooling of local plasma. We get an average temperature decreasing rate of $-9000$
K s$^{-1}$ in the catastrophic cooling phase. In contrast, the cooling rate before catastrophic
cooling is $-3000$ K s$^{-1}$. As a result of catastrophic cooling, the local temperature decreases
from 0.2 MK to 0.02 MK within half a minute (Fig. 5a), while the local number density
increases by one order, from $10^{10}$ cm$^{-3}$ to $10^{11}$ cm$^{-3}$ (Fig. 5b).

A quasi-periodic pulsation (QPP) with a period of $\sim 3$ minutes appears in the maximum
density curve, just after the rain condensation disappeared from the PFL system. This QPP
is caused by the injected flows mentioned in the previous section, refilling and reheating
the PFL. The density variation due to these flows along a field line is shown in Fig. 4c.
Injected flows propagating from one footpoint to the other produce reflected slow mode
waves. Such a process has previously been studied in [39] for isolated loop systems. The
sharp density changes in Fig. 4c are shocks ahead of the injection flows and the wave fronts
of the slow mode waves. Such QPPs hence reflect density variations in the low corona due
to flows or wave propagation. The period of our QPP is close to the time for the slow
mode wave to propagate from one footpoint to the other, as the wave speed is about 300
km s$^{-1}$.
Figure 5: (a): Time evolution of maximum/minimum temperature in the region showing coronal rain from Fig. 4a. (b): Evolution of maximum/minimum number density in the same region. (c): Time-space plot of the number density along a field line with $y = 0$ footpoints at $x = \pm 24.5$ Mm, after the rain left the studied loop region, and a quasi-periodic oscillation appears. The midpoint of the field lines is at $s = 0$ and negative $s$ indicates the left side.
Coronal rain and dark post-flare loops

In synthesized EUV images of our simulation, coronal loop(s) appear in the gradual phase. An example is shown in Fig. 6 at the 17.1 nm waveband. Interestingly, this loop disappears for about 10 minutes during the evolution, as demonstrated in panels (a) to (e) of Fig. 6. The sudden darkening of the bright EUV loop in our simulation resembles the dark post-flare loop (DPFL) phenomenon, previously observed at the same 17.1 nm passband and with similar timescale of 10 minutes [32]. Observed DPFLs and the disappearing EUV coronal loop in our simulation also share the same time evolution of integral EUV flux: the EUV flux reaches its minimum value when the darkening happens (compare Fig. 3 in ref. [32] and our Fig. 6f). The formation of a darkened coronal EUV loop needs to satisfy one or both of the following conditions: (1) an emission drop in an existing bright EUV loop; (2) an absorption of the background EUV emission [40]. Here we explain how these conditions can be satisfied based on our simulation results.

The role of cool and dense coronal plasma in EUV emission and absorption leading to DPFLs has been emphasized previously [33, 34], with coronal rain observations [11, 12, 13, 14] and our simulation results showing how this cool and dense plasma can be generated in PFLs. The drop in the loop emission is understood from our simulation: loop temperature changes relate to nearby rain condensations. Indeed, the temperature of bright loops in this 17.1 passband (about $10^{5.8}$ K) is not far from the critical temperature for the onset.

Figure 6: (a-e): Time evolution of synthetic EUV 17.1 nm images. The regions in cyan have temperatures lower than 0.1 MK. (f): Time evolution of the integral EUV 17.1 nm flux from a region $y > 5$ Mm. Red vertical dashed lines in panel (f) give the corresponding times of panels (a-e).
of catastrophic cooling (this is density and temperature dependent, but generally happens below 2 MK according to [41]). Condensations can be triggered by thermal instability near bright loops and these suddenly formed structures grow fastest across magnetic field lines (counterintuitive due to the field-aligned thermal conduction, but see [22, 29, 30, 42]). Rain that forms near (Fig. 6a-b), and ultimately inside (Fig. 6c) the bright coronal loops, thus causes the darkening as illustrated in Fig. 6c-d. Once condensation happens, a lot of plasma will collect into a small region, so the plasma density elsewhere in the loop decreases. To maintain pressure balance, these evacuated loop regions will increase in temperature, so EUV brightness decreases due to these combined temperature and density changes. Ultimately, the loop refills and brightens once more (Fig. 6e).

Summary

To fully understand coronal rain in PFLs and the mass and energy budget in the gradual phase of solar flares, we performed the first flare simulation from onset all the way into the long duration post-flare phase. Post-flare coronal rain successfully and repeatedly forms. The flare-induced rain is a result of catastrophic cooling by thermal instabilities, and our simulation shows successive rain formation at increasing heights in the PFL configuration. Falling rain blobs into the chromosphere lead to sudden mass drops in PFLs, but their mass increases again due to spontaneously forming injection flows. Therefore, the coronal rain events do not accelerate the PFL mass loss in the longer term. Such longer term mass loss is more determined by the change of the gravity scale height due to the cooling of PFLs.

Both thermal conduction and radiative losses contribute to the energy budget in PFLs. Thermal conduction dominates the PFL energy loss at the beginning of the gradual phase. Thereafter, it becomes less efficient than radiative losses, owing to decreases in loop temperature and in temperature gradient. However, thermal conduction can efficiently recover again after a condensation falls to the chromosphere, as the loop reaches again a high temperature. In this phase, an emptied loop refills and can show a slow-wave related QPP.

We showed that the formation of DPFLs can result from post-flare rain condensations. Condensations change loop temperatures and can make existing bright EUV loops temporarily disappear for several minutes. This timescale of EUV loop darkening is identical to observed DPFLs.

Methods

Simulation setup

We perform the simulation with the open-source MPI-AMRVAC code [43, 44]. The simulation is 2.5D, where the domain is 2D but all vector quantities have three components.
The simulation domain is given by \(-75 \text{ Mm} \leq x \leq 75 \text{ Mm}\) and \(0 \leq y \leq 100 \text{ Mm}\). This simulation box has an initial resolution of \(96 \times 64\), but an equivalent high resolution of \(3072 \times 2048\) is achieved with our block-adaptive mesh. The governing equations are the magnetohydrodynamic (MHD) equations with effects of gravity, thermal conduction, radiative loss and magnetic field dissipation due to resistivity included, also shown in [7] (the source terms related to fast electrons have not been activated here). The new multidimensional field-line-based transition region adaptive conduction (TRAC-L) method is adopted to properly handle the chromosphere-corona interaction at affordable resolution [45].

A relaxation has been done to obtain a static pre-flare atmosphere before we perform the flare simulation. A background heating is required to offset the energy losses due to radiative cooling and thermal conduction. Inspired by [46], this background heating is a function of initial and spatio-temporally evolving values, given by

\[
H_b(x, y, t) = 0.5 \{ \tanh[(y - h_{\text{tra}})/h_a] + 1\} N_{e,0}(y) N_e(x, y, t) \left( \frac{T_0(y)}{T(x, y, t)} \right)^2 G(T_0(y)),
\]

where \(h_{\text{tra}} = 3 \text{ Mm}, h_a = 0.1 \text{ Mm}, N_e\) indicates number density, subscript 0 indicates the \(t = 0\) initial value and \(G(T)\) is the radiative cooling curve adopted in our simulations. The cooling curve from [47] is used. The initial vertical temperature \(T_0(y)\) profile in [48] (model C7) is employed. The number density at \(y = 40 \text{ Mm}\) is set to \(2 \times 10^9 \text{ cm}^{-3}\) and the initial density profile is calculated based on hydrostatic equilibrium. In the relaxation stage, a uniform vertical magnetic field is adopted. A numerically static atmosphere is obtained after a relaxation time corresponding to 3.5 hours. The local number density at \(y = 40\) Mm decreases to about \(10^9 \text{ cm}^{-3}\) after this relaxation. The final instantaneous background heating rate of this relaxed stage is saved and then used in the subsequent flare simulation.

After the relaxation, the magnetic field configuration is changed. The magnetic configuration from [46] is employed then, given by

\[
B_x = 0,
\]

\[
B_y = \begin{cases} 
-B_0, & x < -\lambda \\
B_0, & x > \lambda \\
B_0 \sin[\pi x/(2\lambda)], & \text{else}
\end{cases}
\]

\[
B_z = \sqrt{B_0^2 - B_y^2},
\]

where \(B_0 = 30 \text{ G}\) is the new initial magnetic field strength and \(\lambda = 10 \text{ Mm}\). Such a configuration allows magnetic reconnection. A three-stage resistivity strategy is then activated. A spatially localized resistivity inside the initial current sheet triggers magnetic reconnection in the first stage. This localized resistivity is given by

\[
\eta(x, y, t < t_{\eta1}) = \begin{cases} 
\eta_1 [2(r/r_\eta)^3 - 3(r/r_\eta)^2 + 1], & r \leq r_\eta \\
0, & r > r_\eta
\end{cases}
\]

where \(r = \sqrt{x^2 + y^2}\) is the distance from the observer, \(\eta_1 = 0.01 \text{ cm}^2 \text{ G}^{-1} \text{ s}^{-1}\) is the resistivity. 

where $\eta_1 = 0.1$, $r = \sqrt{x^2 + (y - h_\eta)^2}$, $h_\eta = 40$ Mm, $r_\eta = 2.4$ Mm and $t_{\eta 1} = 31$ s. In the second stage, we use an anomalous resistivity given by

$$\eta(x, y, t_{\eta 1} < t < t_{\eta 2}) = \begin{cases} 
0, & v_d \leq v_c \\
\min\{\alpha_\eta(v_d/v_c - 1) \exp\left[(y - h_\eta)^2/h_s^2\right], 1\}, & v_d > v_c
\end{cases}$$

(6)

where $\alpha_\eta = 1 \times 10^{-3}$, $h_s = 10$ Mm, $t_{\eta 2} = 7.78$ min, $v_d(x, y, t) = J/(eN_e)$ and $v_c = 128,000$ km s$^{-1}$. The resistivity is set to zero in the third stage $t > t_{\eta 2}$ to force the flare to enter the gradual phase, where only numerical dissipation happens. The resistivity strategy used in our first and second stage is similar to that in [49].

We employ symmetric boundary conditions for number density, pressure and magnetic field components, while anti-symmetric conditions are employed for velocity components at the left and right boundaries. At the upper and bottom boundaries, density and pressure are fixed to their initial values. The magnetic field components at the bottom boundary are also fixed to the initial values. An anti-symmetric condition is applied for the $x$-component of the magnetic field at our upper boundary, while the other two components of the magnetic field employ symmetric conditions there. The velocity at the upper boundary is set to zero. Anti-symmetric conditions are employed for the velocity components at the bottom boundary.

The SXR emission is calculated with the method reported in [50]. The EUV emissions are calculated with the contribution function provided by the CHIANTI database and the optically thin assumption [51].

**Data Availability**

Simulation data are available on request to W.Z.R. (wenzhi.ruan@kuleuven.be).

**Code availability**

The simulation is performed with the open-source AMRVAC code [43, 44], which is available in website http://amrvac.org.

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Author contributions

W.Z.R performed the simulation and wrote the first draft. Y.H.Z contributed to the implementation of the TRAC-L method and revision of the paper. R.K initiated the study, supervised the project, led the discussions and contributed to revision of the paper. All authors contributed to discussions.

Competing interests

The authors declare no competing interests.