

## Coronal rain and showers in the solar atmosphere

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### Abstract

As a result of thermal instability, solar coronal plasma can condense and fragment into heavy, cold blobs which subsequently fall towards the solar surface. Early hydrodynamic (1D) models showed that this can happen in footpoint heated coronal loops, that can show recurrent rain events. We made true multi-dimensional models of coronal rain, where we started off [1, 2] in 2.5D (assuming invariance along the sheared arcade), to then explore the process in its 3D manifestation [4, 6]. Much of the insights gained from 1D studies still persist, with e.g. the formation of siphon flows causing rebound shocks appearing right after the condensations form. However, the growth of coronal rain blobs happens faster in directions across neighboring field lines, which evolve similarly under footpoint heating. The rebound shocks develop into curved shock fronts that reflect the formation history of condensations on adjacent field lines. We find that coronal rain self-consistently establishes counter-streaming flows, when a blob and its blob-corona transition region gets torn up into fragments with low pressure conditions on their connecting sections. These depleted areas drive further siphon flows. In 3D, coronal rain in relatively weak magnetic field regions show clear indications of Rayleigh-Taylor/interchange instabilities, that result in more field-guided blob motions in lower-lying regions. Synthetic images at EUV wavelengths agree with actual observations.

Coronal rain manifests itself throughout the solar corona, especially in active regions, where coronal loops are seen to guide the overall downward motions of cold, blob-like features. Typical scales are of order of a few 100 km, and their temperatures are a factor of 100 below the coronal MK. Recent observational analyses suggest that loops go through repeating heating-condensation cycles, where rain forms with typical velocities up to 180 km/s [3]. Many modeling efforts have used their virtually field-guided aspect to study coronal rain formation and dynamics on a given magnetic fieldline, such that only pressure and (projected) gravity appear as forces acting on the blobs. A viable scenario for rain formation is one where a coronal loop system is footpoint heated, such that chromospheric matter gets evaporated into the loops and their changing density-temperature variation ultimately triggers thermal instability. The density-temperature variation of the optically thin radiative cooling happening in the corona is

the main ingredient for the instability, since regimes exist where a drop in temperature leads to more effective cooling, in combination with the typical density squared dependence of radiative processes. Here, we summarize the main findings from true multi-dimensional single fluid magnetohydrodynamic models [1, 2, 6]. All are using the open-source MPI-AMRVAC code with automated grid-adaptivity to resolve the internal blob structure [5].

## 2.5D model findings

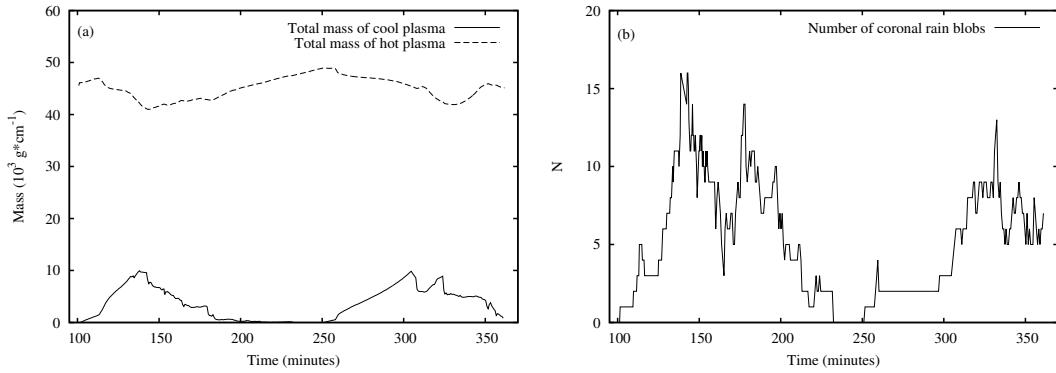


Figure 1: (a) Evolution of mass of hot and cool plasma in the corona versus time. (b) Number of coronal rain blobs as function of time. From [2].

In 2.5D settings [1, 2], we investigated the thermodynamic evolution of a bipolar arcade, where the field is initially a linear force-free setup where all field lines make a constant angle of  $30^\circ$  with the neutral line. To realize a chromosphere-transition region-corona configuration, we augment it with a hydrostatic equilibrium that has a temperature profile consistent with a constant vertical thermal conduction flux. Since field-aligned thermal conduction is used in the simulations, along with local radiative loss prescriptions, this initial state needs to relax to a true equilibrium where the heat loss is balanced by a background heating term, and this relaxation is typically performed for more than one hour of physical time. The endstate contains an overall quasi-static corona, where the transition region is situated at about 3-5 Mm height. This state is then subject to further extra heating, in a pre-selected bundle of field lines of about 12 Mm width (at each side). What follows is a gradual evolution that brings the coronal part of the heated loops closer to thermal instability, and after 100 minutes, we find the onset of coronal rain. Figure 1 quantifies the mass exchange between hot and cool coronal plasma, as well as the number of condensations, for the entire 270 minute period where coronal rain is seen. This long term simulation clearly encompasses two full heating-condensation cycles, which can repeat multiple times, very much like in the observations.

What the simulations also reproduce very well is the observed spread in width and length, reaching an average width of 400 km, while the blob lengths can be a few Mm. The blob dy-

namics is influenced by the siphon flows that get established as soon as the condensations form, and it was shown [2] how blobs can thereby establish two-sided or one-sided rebound shocks separating from their blob-corona-transition region structure. One-sided, curved shock patterns can be noticed on those blobs that happen to get born on field lines already supporting other blob structures, especially when the blobs form away from the loop apex. This is happening throughout the evolution, and one can identify condensations that evaporate in situ, get siphoned over the loop apex, or fragment into or merge with other blobs as they descend.

As blobs impact on the transition region, we find once more rebound shocks with fast upflows (50 km/s) that invade the then evacuated field line bundle. As blobs form and descend at different speeds and locations, this establishes a strong pattern of counter-streaming flows throughout neighbouring field lines. These in turn cause further blob deformations and fragmentations, making the whole process truly multidimensional in nature.

### 3D model findings

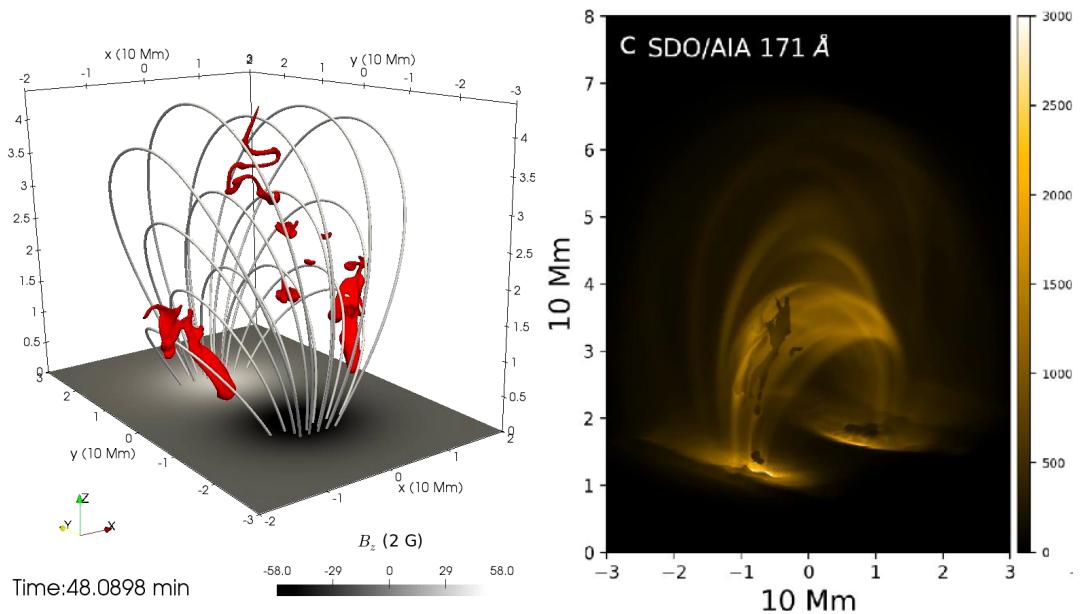


Figure 2: *Coronal rain in a (weak) bipole field. Left shows the magnetic field configuration as well as the location of cool blobs as isosurfaces of density. At right, we show a virtual view in EUV wavelengths, when several blobs merged into a coronal shower. Adapted from [6].*

In Xia et al. [6], we performed 3D simulations of a footpoint heated bipolar arcade. The bottom field strength reaches values up to 120 Gauss, and the additional heating prescription scales with the local vertical magnetic field component squared, and decays exponentially above 4 Mm. The box size is  $40 \times 60 \times 60 \text{ Mm}^3$ , and we simulate coronal rain dynamics for more than 2 hours. The simulation confirms the 2.5D studies as far as the blob onset and rebound shock dynamics is concerned, but shows that the first condensation grows fastest across the field lines.

Again neighboring loops evolve quasi-similarly, and a fairly large condensation develops in the arcade loops above the polarity inversion line from about 13 minutes onwards. The local plasma beta condition at that altitude (40 Mm height) is about 0.5, and together with the density inversion realized by the condensation, we witness this condensation to fragment due to clear Rayleigh-Taylor instability development. Contrary to many observations of coronal rain in active region fields, the initial blobs are then first seen to meander down the field in a fairly erratic manner, with averaged speeds going up to 20 km/s. A snapshot at about 50 minutes into the process is shown in Fig. 2, where the Rayleigh-Taylor deformation is still visible in the highest blob present. This brings the condensations down to lower beta regions, from which point all blobs are seen to follow the lower-lying field lines. In the later part of our simulation, a distinct mass drainage event where multiple blobs have merged into a curtain of cold, dense plasma sliding down the lower field lines can be qualified as a coronal rain shower, spread over a width of several Mm. A virtual extreme ultraviolet view is shown at right in Fig. 2, and at that time only lower lying field lines contain raining plasma. The maximal speeds throughout the coronal rain event reach up to 120 km/s, in agreement with observational values. The 3D study does demonstrate that the development of shear flows due to pressure variations in the vicinity of (merging) blobs still greatly affects their deformation. The shear flows enhance the blob elongation on its way down.

## Conclusion

Simulations of coronal rain reproduce many observational facts, in terms of blob sizes and statistics, but also their fairly complex thermodynamic evolutions. In bipolar arcades [1, 2, 6], we find that multiple cycles of heating-condensation occur within hours. Since we parametrized the unknown coronal heating, we may improve our simulations by adopting more physics-based heating prescriptions, and/or vary the magnetic field complexity to e.g. quadrupolar field setups [4]. Ultimately, one targets specific active region evolutions, using extrapolated field information, to see how condensations form as a consequence of the rapid energy release occurring during flare events.

## References

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