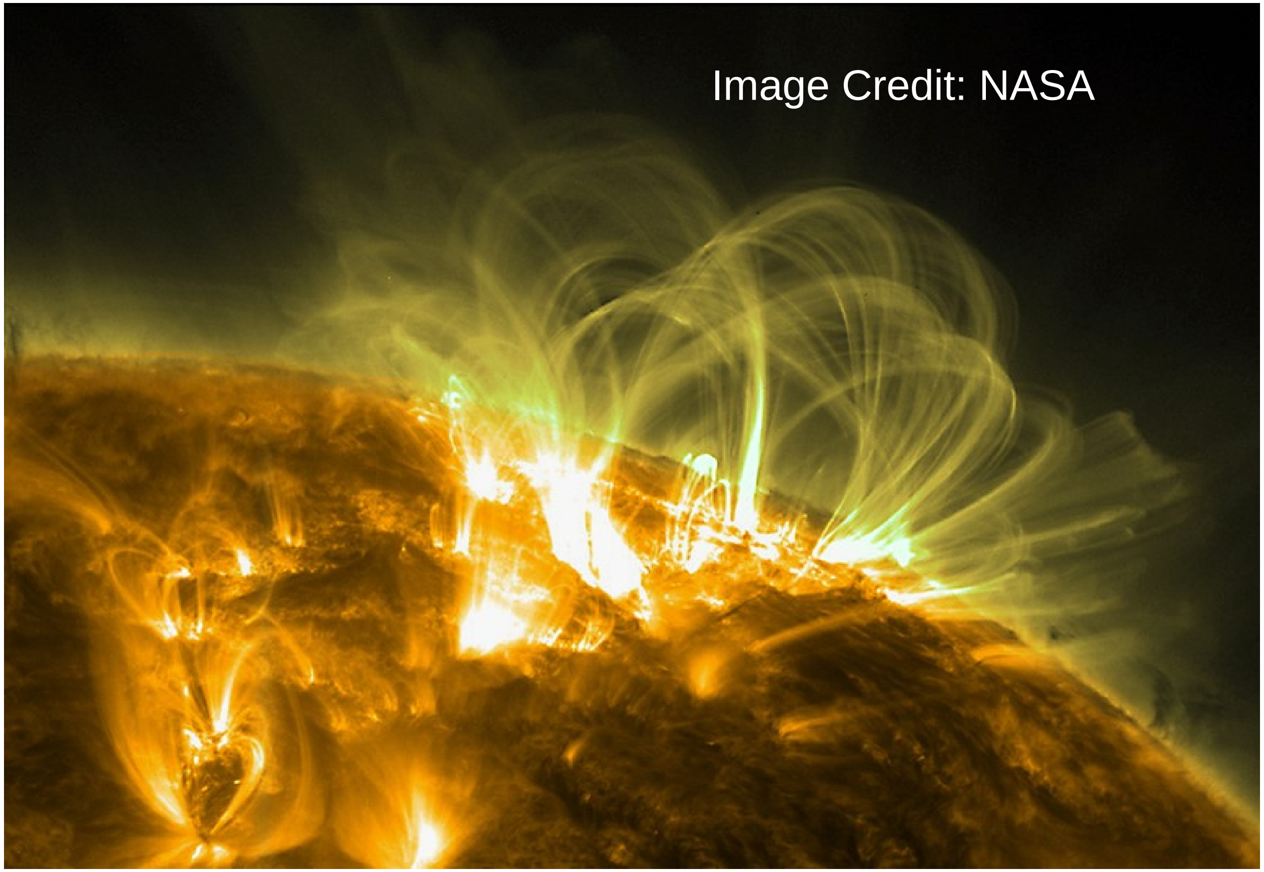

Flows in Enthalpy Based Thermal Evolution of Loops.

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Field aligned simulations of coronal loops.

- **Solar corona is filled with a myriad of loop like structures.**
- **After heating event has occurred, magnetic field configuration doesn't change much.**
- **Field aligned 1D simulations are well justified for studying response of loop to a heating event.**

Why are faster alternatives needed ?

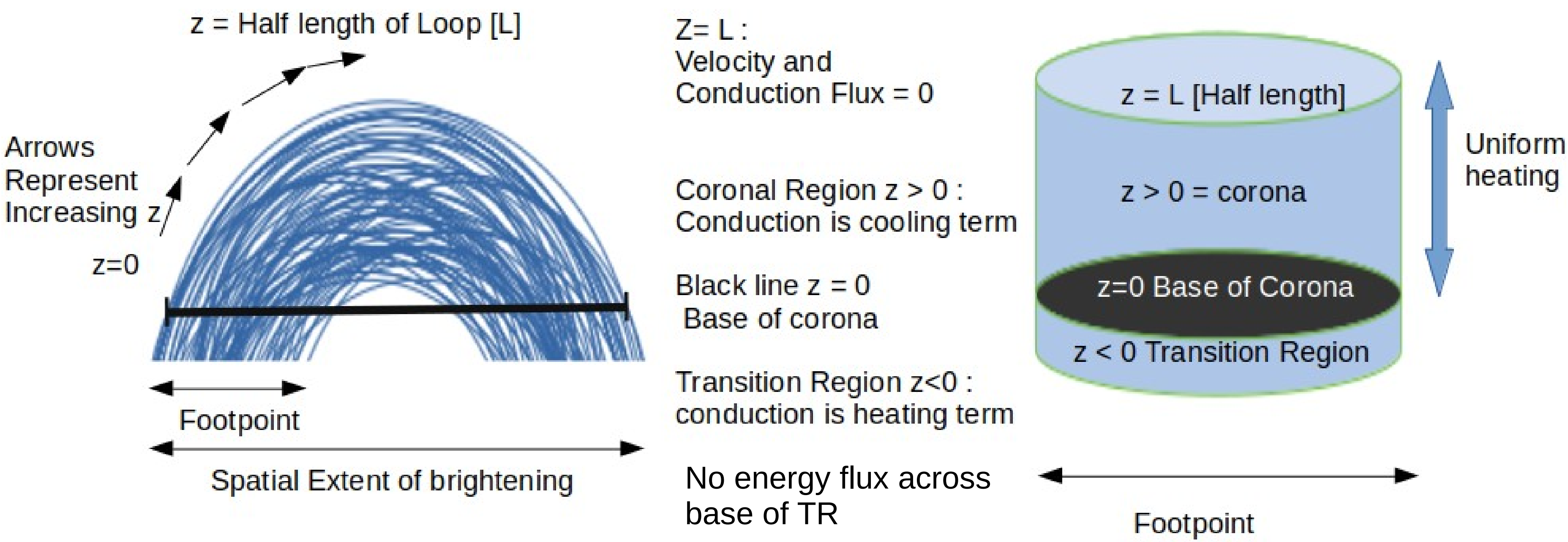
Factors which make field aligned simulations computationally expensive.

- **Observed loops are multistranded.**
- **Cross field thermal conduction is negligible.**
- **Each strand needs to be modeled indepedently.**

Faster alternatives are better suited for some studies.

- **Large number of runs are needed for parametric studies which study the response of a wide range of loops to a wide range of heating functions.**
- **Approximate response of loop to heating function suffices.**
- **Study of realistic multistranded system for large duration of time is beneficial.**

0D simulations of coronal loops.



- **Solves for instataneous coronal averages of density, pressure, temperature.**
- **Solves for velocity at coronal base of loop.**
- **Solves for instantaneous DEMs from corona and transition region.**

EBTEL - Most commonly used 0D model.

Klimchuk et al. 2008; Cargill et al. 2012 a,b; Barnes et al. 2016, Cargill et al. 2021

- **Flows are assumed to be subsonic throughout.**
- **Not a good approximation in impulsive phase in many cases.**
- **In some cases Mach numbers produced by EBTEL may exceed unity, despite field aligned simulations showing subsonic flows.**
- **This is an artefact of assuming subsonic flows. For reliable information about nature of flows, this assumption needs to be relaxed.**
- **0D models cannot incorporate physics of shocks, hence it is necessary to predict if nature of flows produced are reliable.**

Goals for this study

- **Ensure that flows produced by 0D simulations are subsonic if field aligned simulations show subsonic flows.**

- **Predict the regime where Mach numbers produced by flows in 0D simulations are unreliable.**

Cases studied.

Table: Simulation parameters such as peak heating rate (2nd column), duration of heating (3rd column) [ALL HEATING PROFILES ARE IN SHAPE OF SYMMETRIC TRIANGLES] , loop half length (4thcolumn), initial electron number density (5th column), initial temperature (6th column), maximum Mach numbers at coronalbase computed by HYDRAD (7th column), EBTEL2 (8th column) and EBTEL3 (9th column) for various test cases.

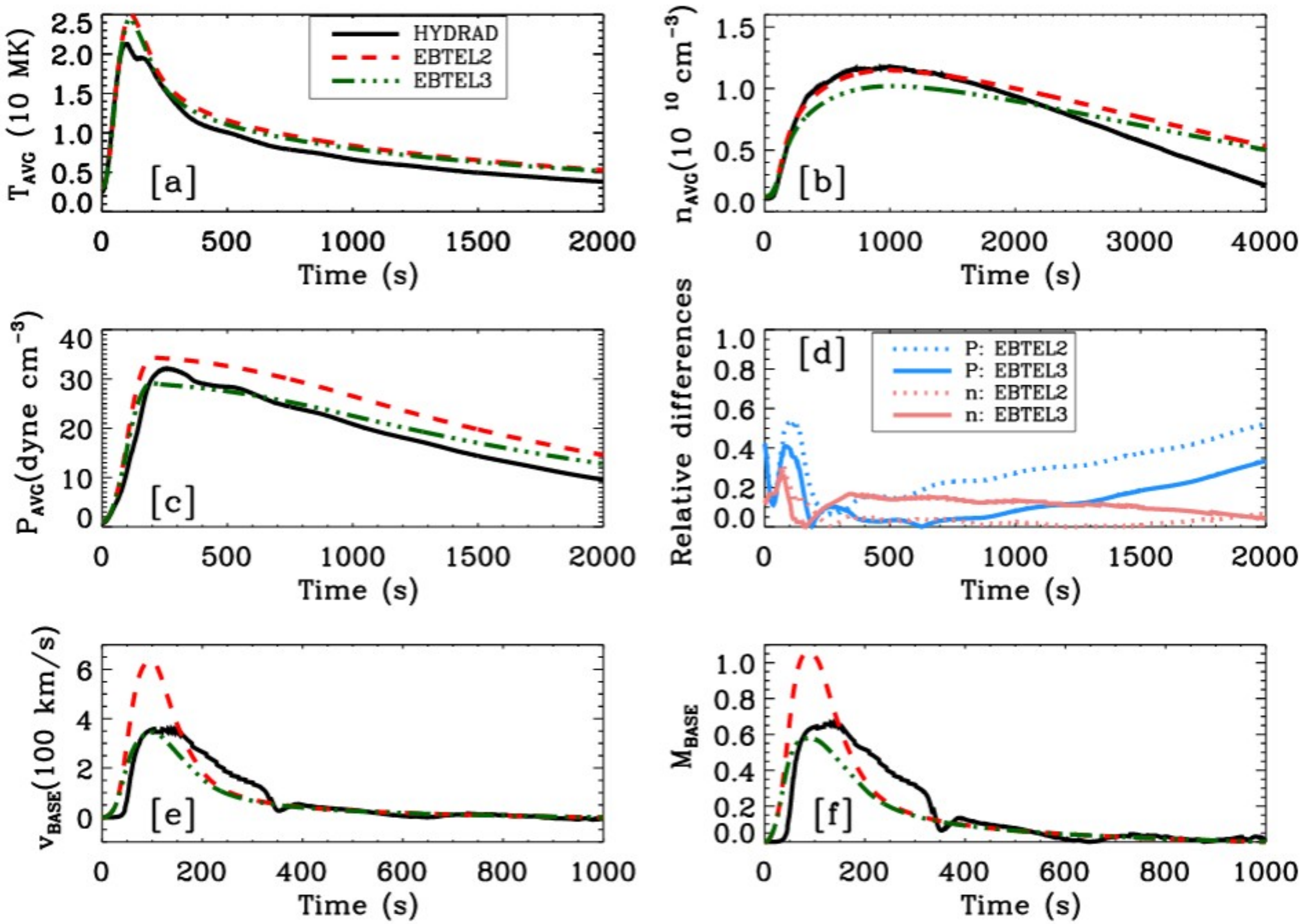
Case	Peak heating rate	Heating Duration	Half length	Initial electron density (n)	Initial Temperature (T)	Maximum M_0	Maximum M_0	Maximum M_0
	[ergs cm $^{-3}$ s $^{-1}$]	[s]	[cm]	[10^8 cm^{-3}]	[10^6 K]	in HYDRAD	in EBTEL2	in EBTEL3
1	0.5	200.0	65.0	11.05	2.51	0.67	1.10	0.58
2	1.5×10^{-3}	500.0	75.0	0.62	0.85	0.57	0.88	0.50
3	1.0×10^{-2}	200.0	25.0	2.46	0.73	0.49	0.61	0.42
4	2.0	200.0	25.0	22.32	2.06	0.55	0.81	0.51
5	1.0×10^{-2}	200.0	50.0	0.84	0.71	0.75	1.32	0.63
6	1.5×10^{-2}	200.0	75.0	0.80	0.92	0.94	1.46	0.65
7	1.0×10^{-3}	200.0	60.0	0.13	0.42	1.15	1.51	0.65

EBTEL2: Single-fluid subsonic 0D description of coronal loops (Cargill et al 2012)

EBTEL3: Generalized single fluid 0D description of coronal loops (Rajhans et al 2021, Under review)

HYDRAD: Field aligned description of coronal loops (Bradshaw et al. 2003, 2006.)

An exemplar case.

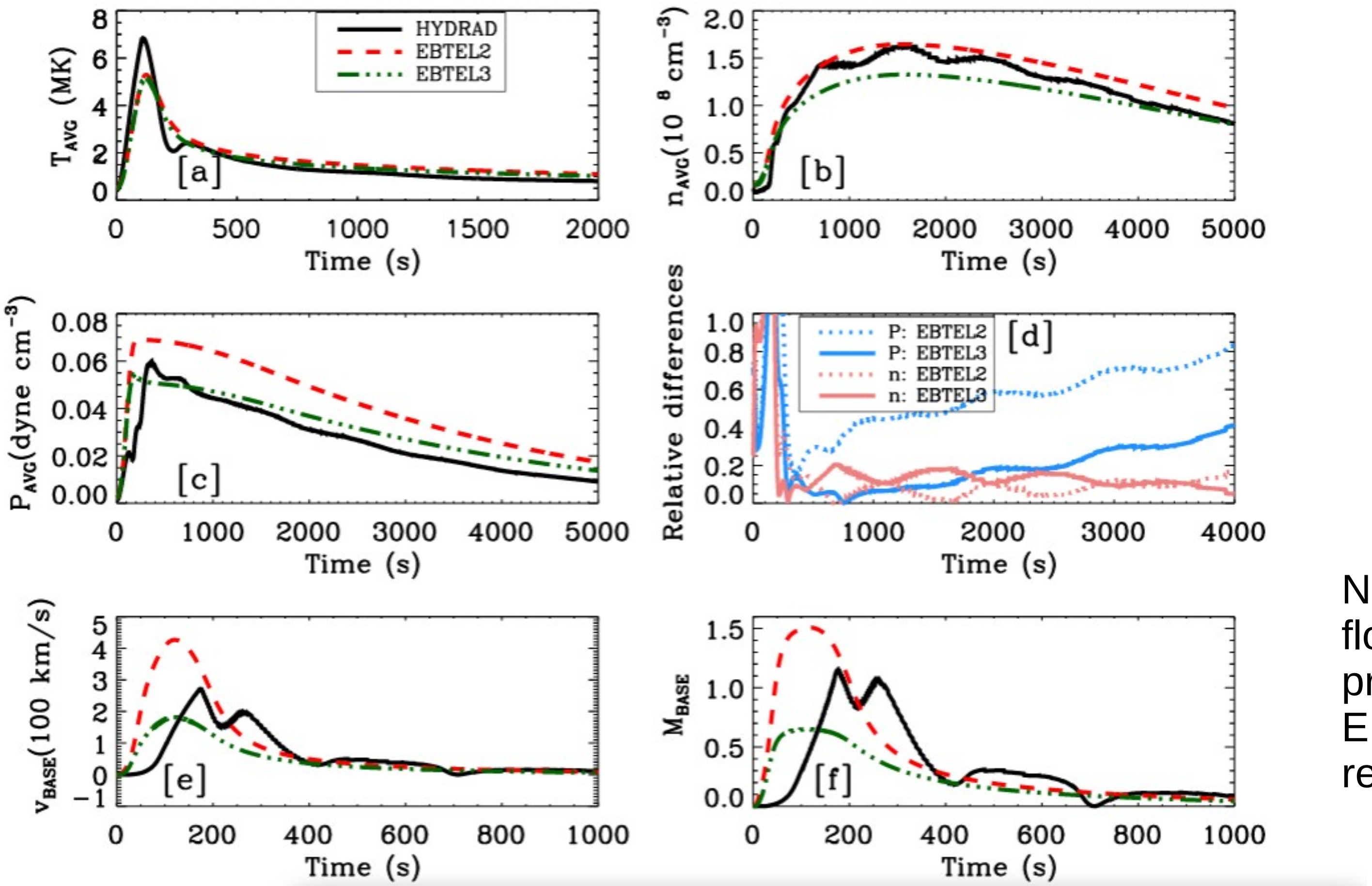


Nature of flows predicted by EBTEL3 reliable.

Case 1: Half length 65 Mm, Initial density and temperature are 11.05×10^{8} cm^{-3} and 2.51 MK, respectively. symmetric triangular heating profile lasting for 200 s, with the maximum heating rate being 0.5 ergs cm^{-3} s^{-1} at t = 100 s.

The curves demonstrate the time evolution of coronal averages of temperature (panel [a]), electron number density (panel [b]), and pressure (panel [c]), the discrepancy in density (red curves) and pressure (blue curves) between HYDRADand those calculated from EBTEL2 (dotted) and EBTEL3 (solid) (panel [d]), velocity at coronal base of loop (panel [e]), and corresponding Mach number (panel [f]).

Another exemplar case.



Nature of flows predicted by EBTEL not reliable.

Case 7: Half length 75 Mm, Initial density and temperature are 0.8×10^8 cm^{-3} and 0.92 MK, respectively. symmetric triangular heating profile lasting for 200 s, with the maximum heating rate being 0.015 ergs cm^{-3} s^{-1} at t = 100 s.

The curves demonstrate the time evolution of coronal averages of temperature (panel [a]), electron number density (panel [b]), and pressure (panel [c]), the discrepancy in density (red curves) and pressure (blue curves) between HYDRADand those calculated from EBTEL2 (dotted) and EBTEL3 (solid) (panel [d]), velocity at coronal base of loop (panel [e]), and corresponding Mach number (panel [f]).

A simple criterion for deciding if Mach numbers produced by 0D simulations are reliable.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Maximum M_0 in HYDRAD	0.67	0.57	0.49	0.55	0.75	0.94	1.15
FWHM of M_0 in EBTEL3 (r_1 in [s])	165.0	396.0	155.0	120.0	193.0	227.0	259.0
FWHM of input heating profile (r_2 in [s])	100.0	250.0	100.0	100.0	100.0	100.0	100.0
(r_1 / r_2)	1.65	1.58	1.55	1.20	1.93	2.27	2.59

- If $r_1 / r_2 \geq 2$, flows produced by EBTEL are not reliable.
- This is due to EBTEL overestimating ratio of electron number density at coronal base and average coronal density.
- This when combined with sum of energy fluxes across coronal base leads to lower velocities and Mach numbers which leads to larger FWHM of the Mach number profiles.

Conclusions.

- 0D simulations offer approximate solutions much faster than detailed field aligned simulations.
- Enthalpy Based Thermal Evolution of Loops (EBTEL) is a commonly used code based on 0D description of coronal loops.
- Existing versions of the description assume the flow to be subsonic throughout.
- Not a good assumption in impulsive phase of many cases. In some cases, Mach numbers produced by EBTEL may exceed unity despite field aligned simulations showing flows to be subsonic.
- This is due to assumption of subsonic flows, which needs to be relaxed. Relaxing the assumption ensures flows in EBTEL is subsonic if flows in field aligned simulations are subsonic.
- Furthermore it is possible to predict the reliability of nature of flows predicted by 0D simulations by simply looking at profiles of heating function and Mach numbers.
- Other quantities computed by EBTEL are still reliable.