Non-Equilibrium Processes in the Solar Atmosphere

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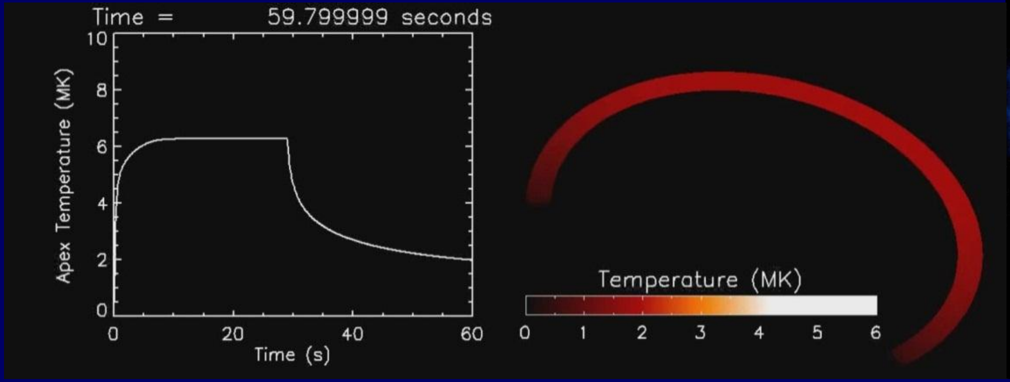
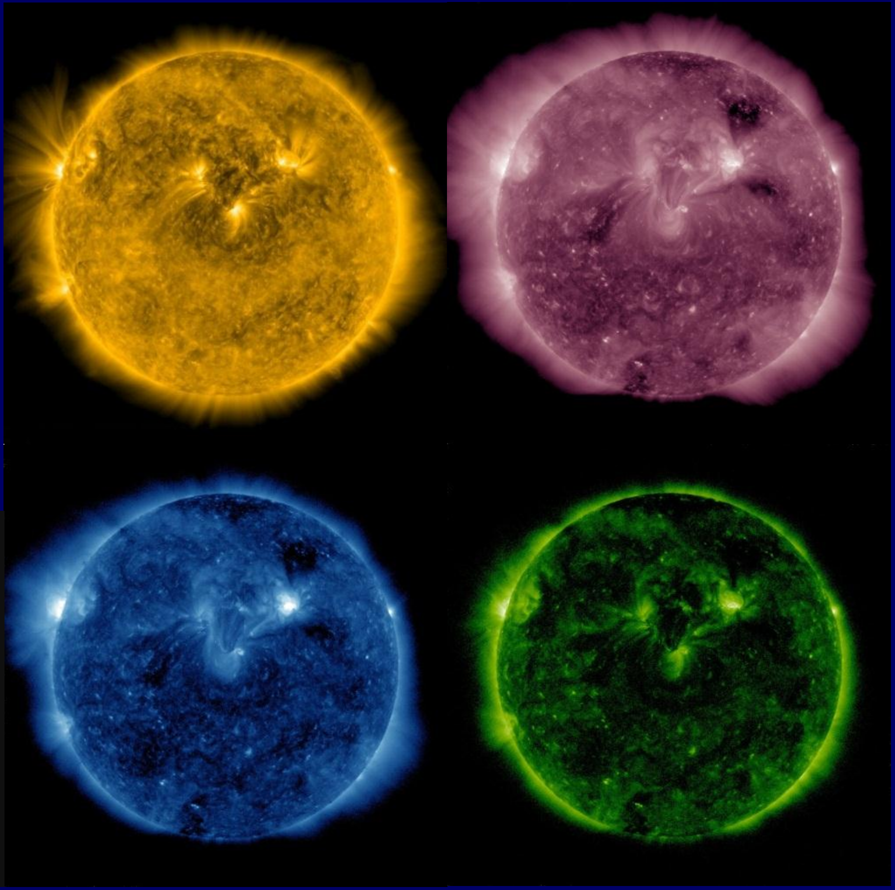
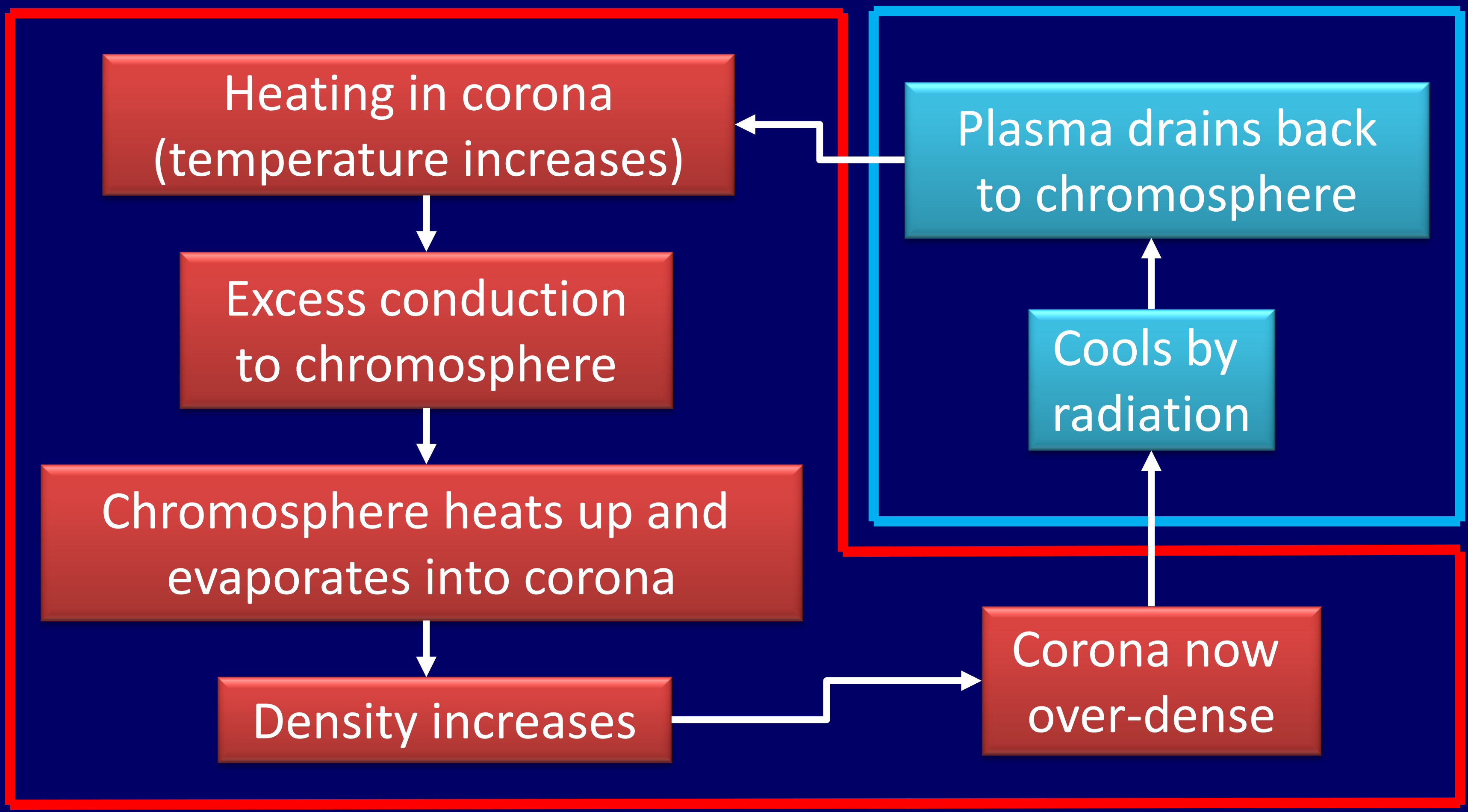




The Heating and Cooling Cycle

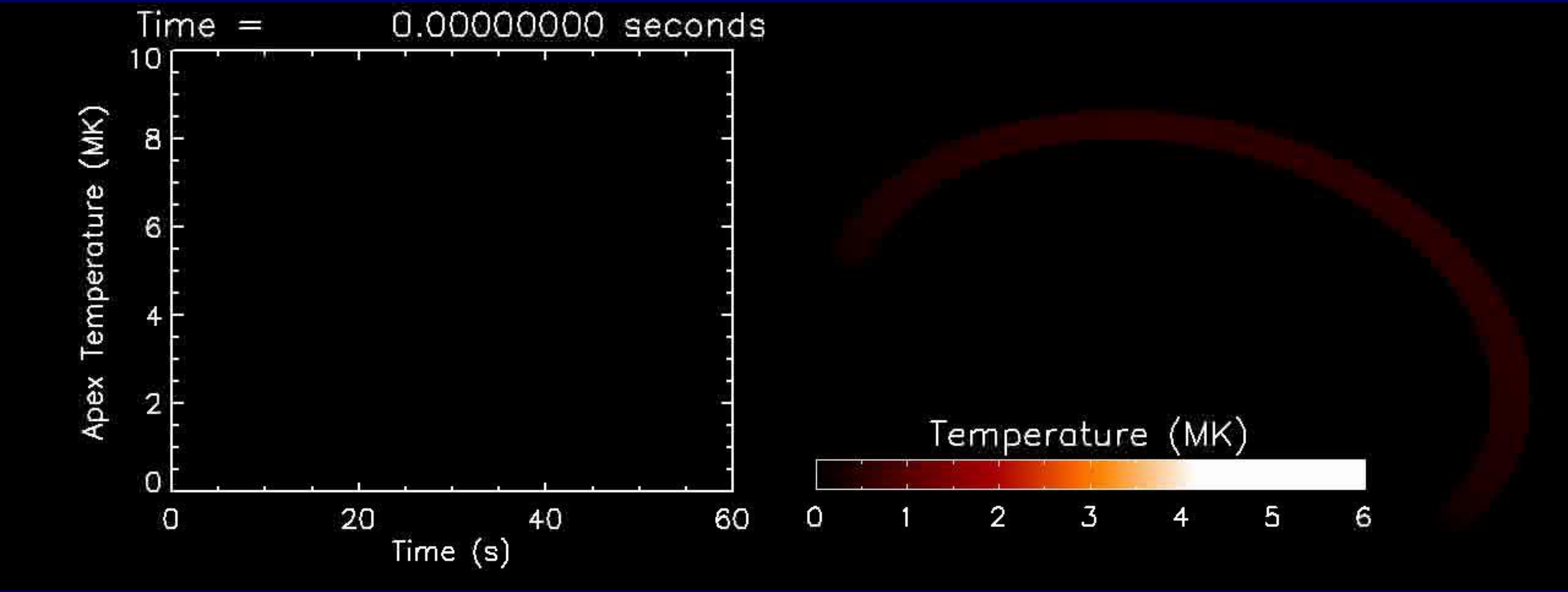
Non-equilibrium processes is rather a wide remit…

Focus on the ionisation state induced during heating and cooling (when $\tau_D < \tau_{I,R}$)



An Impulsively Heated Coronal Loop

A coronal loop heated by some impulsive mechanism:



Period of heating: 30 seconds
Spatial scale: 2000 km
Total energy released: 10^{25} ergs

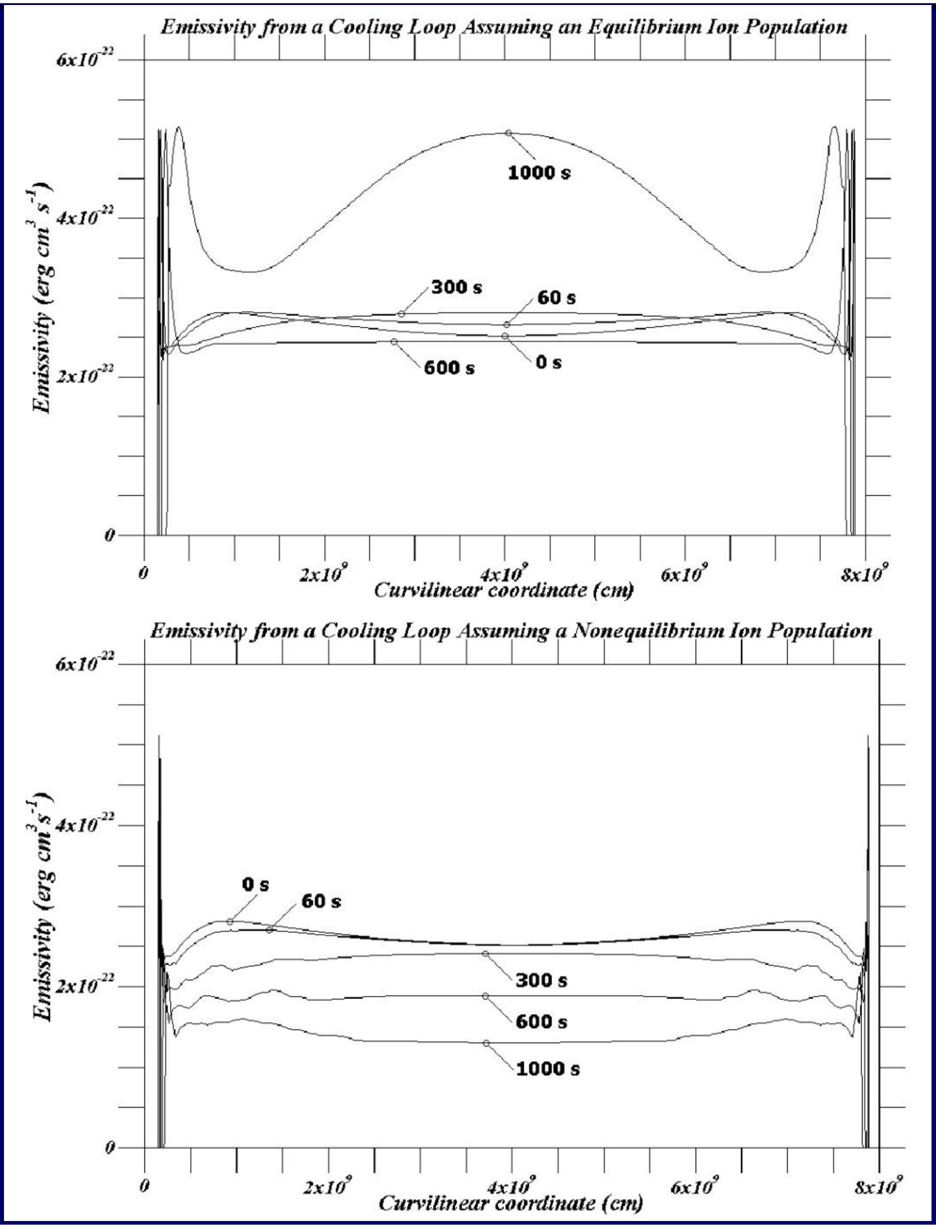
The Early Days - Cooling

Paper I: Non-equilibrium ion populations and radiative emission induced during cooling

A factor of 3 - 5 difference in the radiative emissivity at the foot-points and apex of a gradually cooling loop

Due to the persistence of highly charged states

Approx. 10 minute increase in the cooling time



Bradshaw & Mason, 2003, A&A, 401, 699

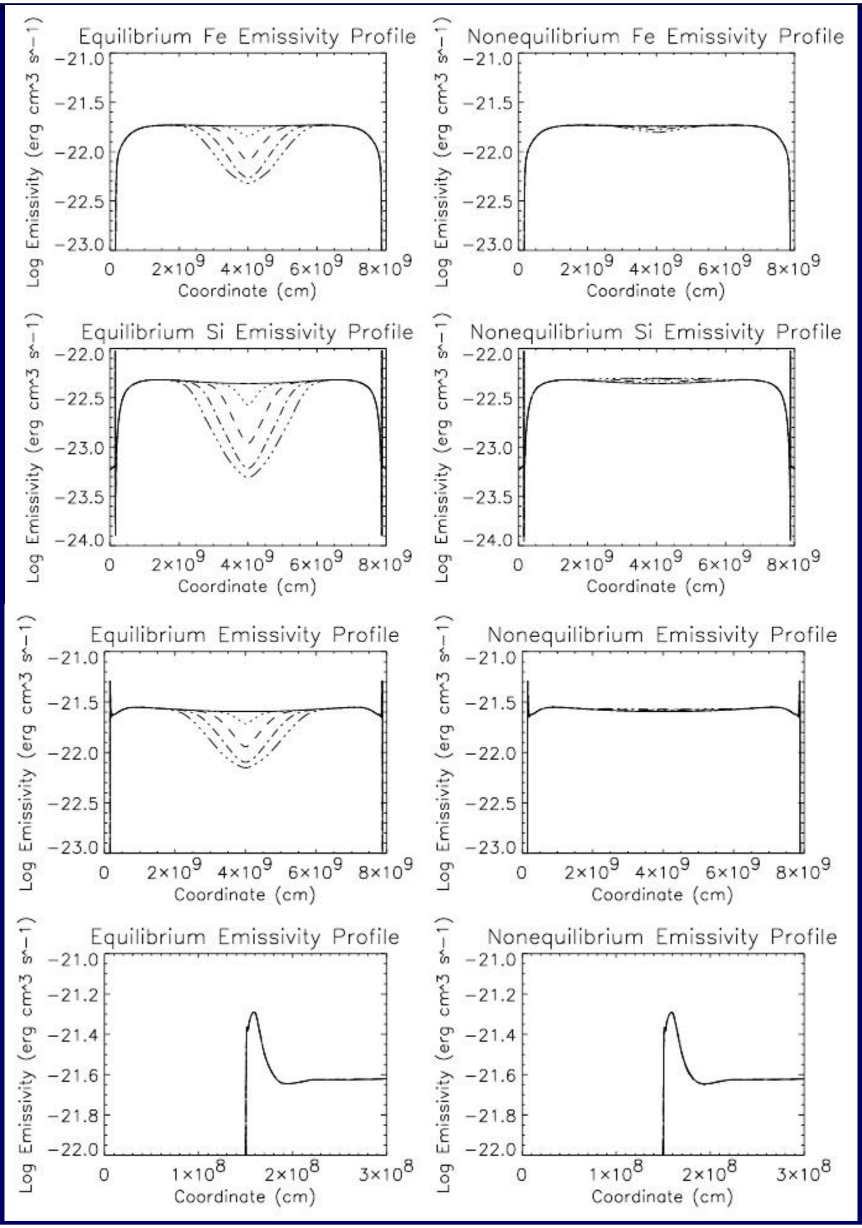
The Early Days - Heating

Paper II: Non-equilibrium ion populations and radiative emission induced during localised and impulsive heating

A factor of 5+ difference in the radiative emissivity in the heated region

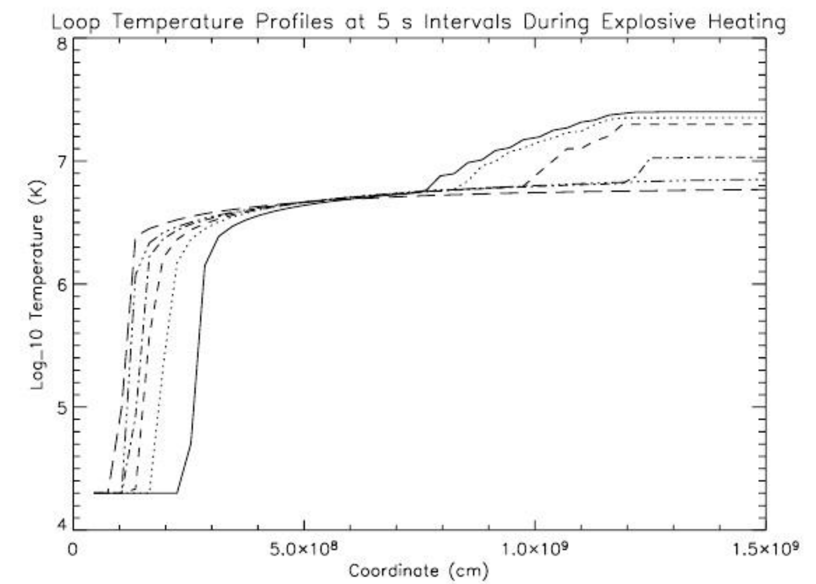
Due to the persistence of more weakly charged states

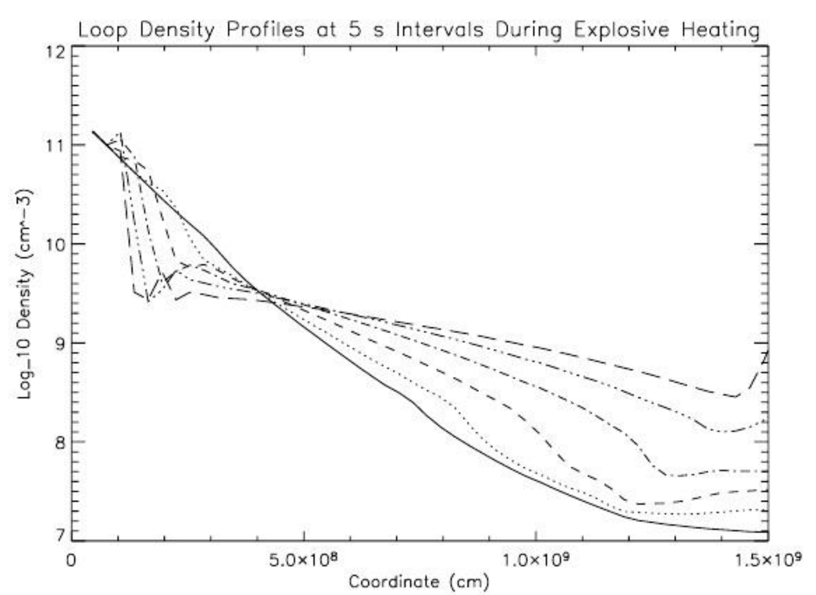
Little observable change in the coronal emission

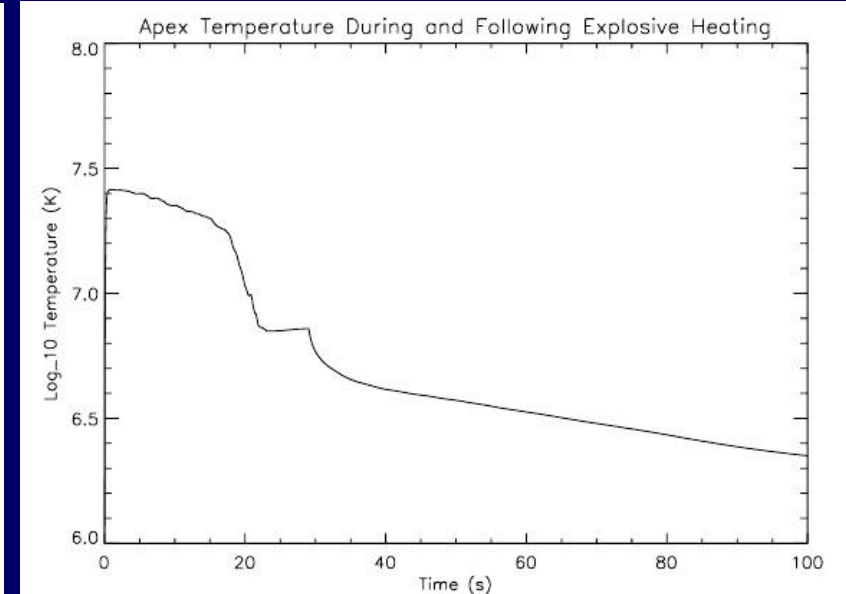


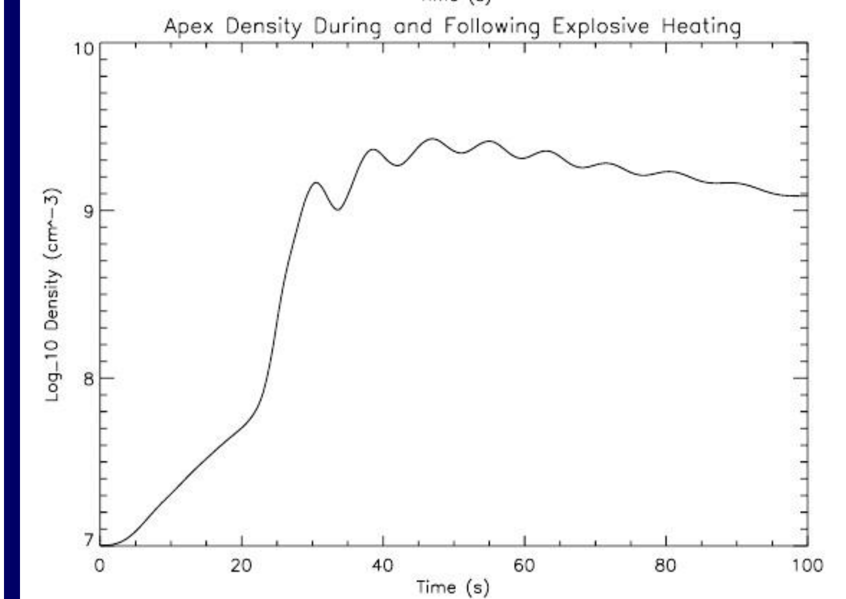
Bradshaw & Mason, 2003, A&A, 407, 1127

Follow-Up – Explosive Heating



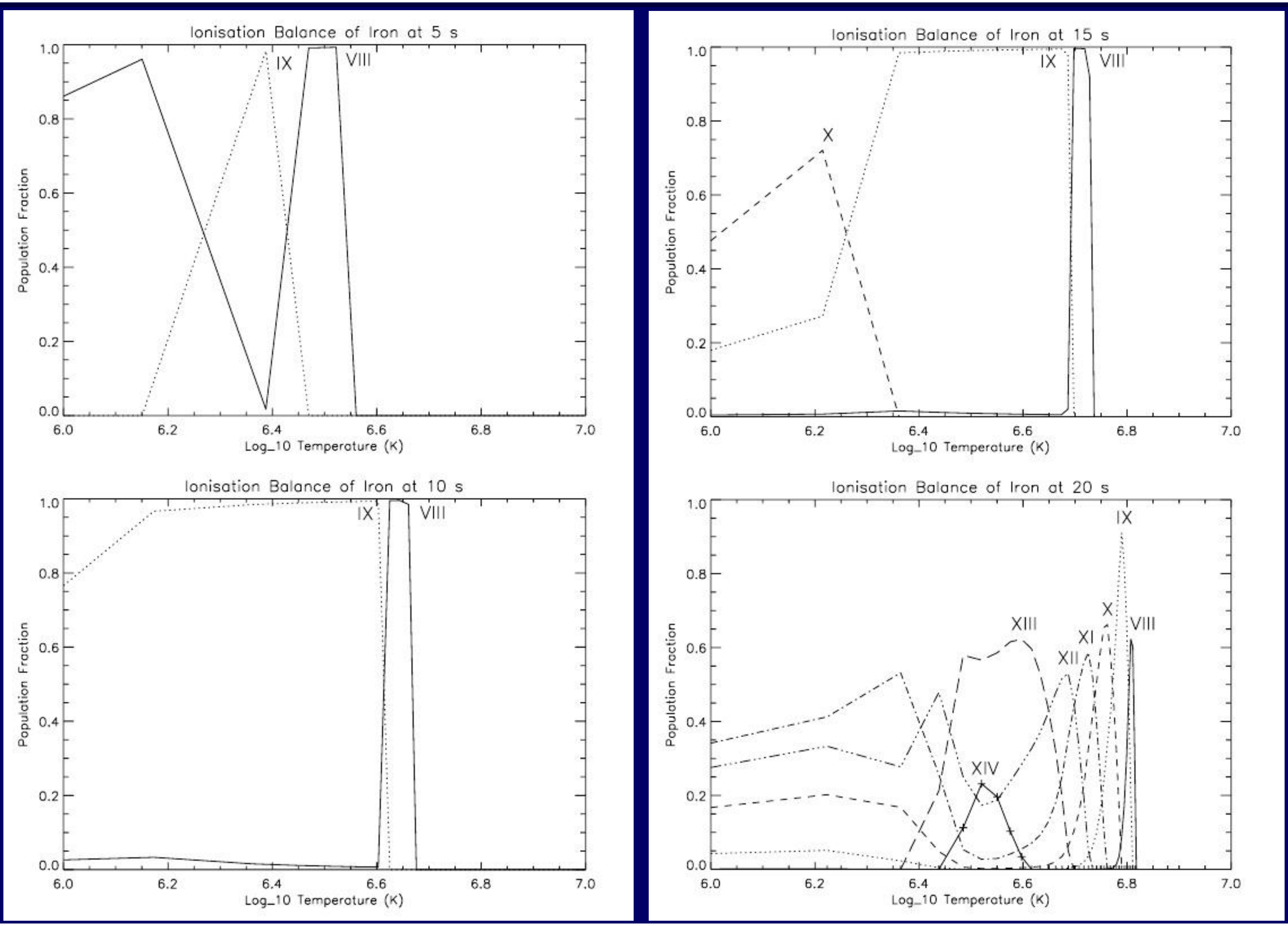






Bradshaw & Cargill, 2006, A&A, 458, 987

Follow-Up – Ionisation State



Bradshaw & Cargill, 2006, A&A, 458, 987

Follow-Up – Forward Modelled Emission

Peak temperature = 25 MK
(reached almost immediately)

Plateau between 20 – 30 s = 6.3 MK
(heating = thermal conduction)

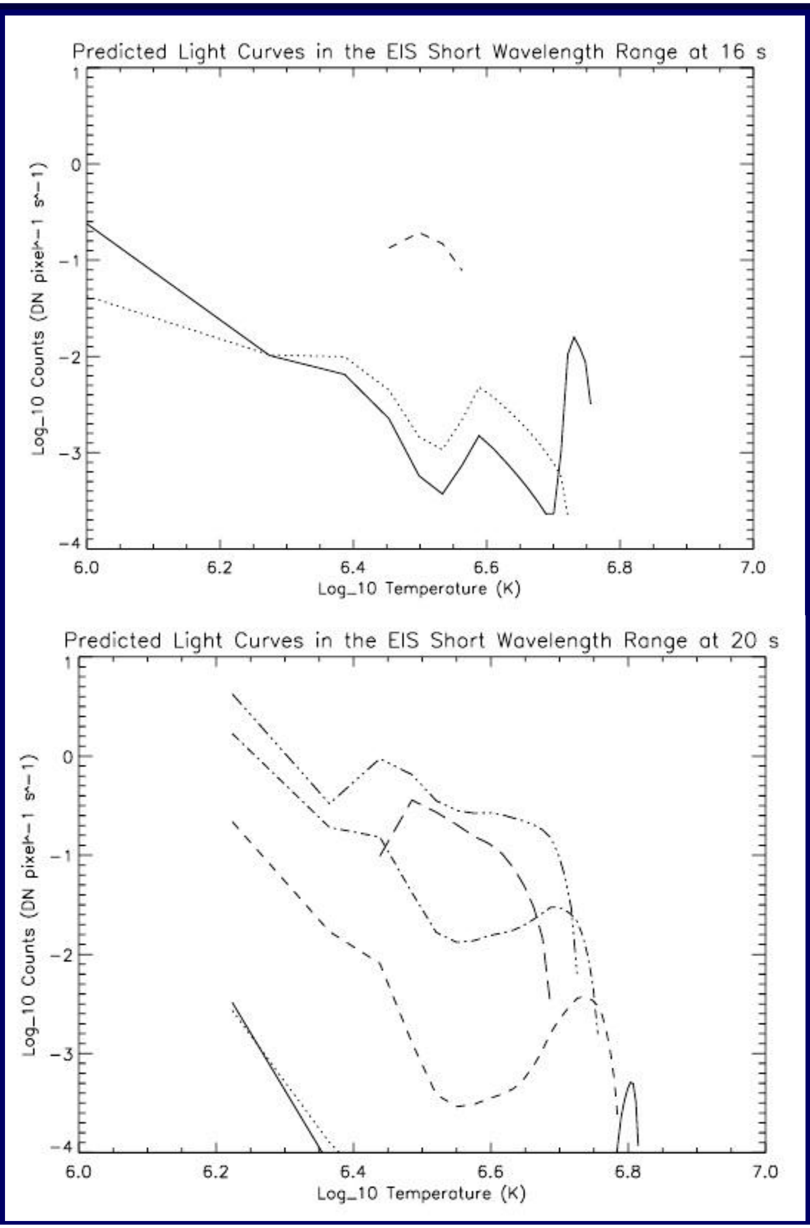
Coronal density increases by 2 OM

Strongly non-equilibrium ion states:

e.g. Fe VIII at 6.3 MK (0.4 MK)
Fe IX at 1.6 – 5 MK (0.6 MK)

No evidence of hot (T > 10 MK) emission during first 20 s

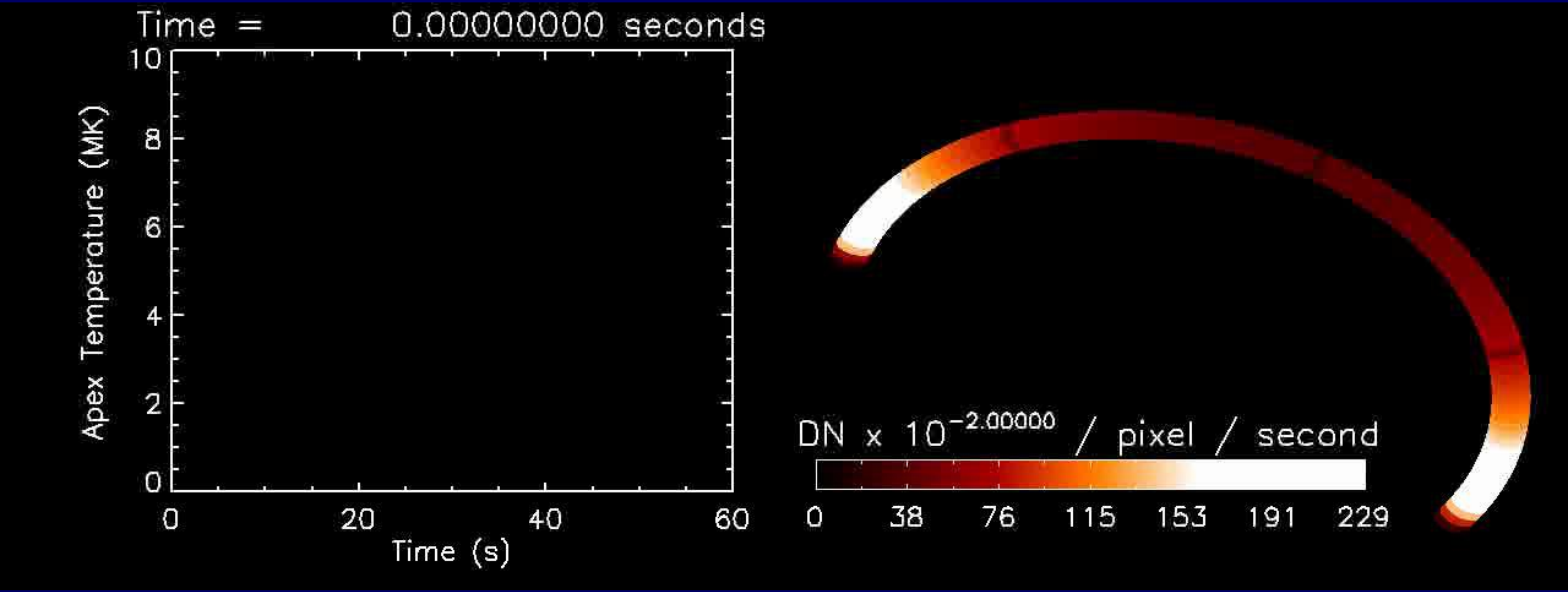
Strongest signature at 20 s Fe XII (1.6 MK) and Fe XIII (1.6 MK)



Bradshaw & Cargill, 2006, A&A, 458, 987

An Impulsively Heated Coronal Loop

Synthesised emission for Hinode-EIS, Fe VIII to XVII:



Effective ion temperature << electron temperature
No high (or low) temperature coronal emission observed
Only the foot-points are visible

Ongoing – Multi-Stranded Loops

So far only impulsive heating of monolithic loops has been discussed

In reality, loops likely to be composed of sub-resolution strands

How does this change matters?
(accounting for non-equilibrium processes)

Construct a multi-stranded loop from a single numerical run by assuming:

- Each stage of evolution corresponds to a new strand
- There are many similarly evolving strands
- Loop sufficiently long lived that at least one strand has undergone a single cycle of heating and cooling
- Yields a single snap-shot in the time evolution of the loop

Ongoing – Numerical Experiments

Table 1: A summary of the numerical experiments relating to: the initial plasma conditions [$2L$, $n_a(t=0)$, $T_a(t=0)$]; the properties of the impulsive heating events [H, t_H]; and the apex density, and the electron and ion temperatures reached at the end of heating [$n_a(t=t_H)$, $T_{a(e)}(t=t_H)$, $T_{a(i)}(t=t_H)$].

#	$2L$ [Mm]	$n_a(t=0)$ [cm^{-3}]	$T_a(t=0)$ [MK]	H [erg cm^{-3} s^{-1}]	t_H [s]	$n_a(t=t_H)$ [cm^{-3}]	$T_{a(e)}(t=t_H)$ [MK]	$T_{a(i)}(t=t_H)$ [MK]
1	20	10^7	0.15	0.05	10	2.2×10^7	4.60	0.16
2	20	10^8	0.38	0.10	10	1.3×10^8	4.80	0.41
3	20	10^8	0.38	0.10	30	6.0×10^8	5.20	0.71
4	20	10^8	0.38	0.10	100	3.2×10^9	6.00	5.40
5	20	10^8	0.38	0.10	300	2.4×10^9	5.80	4.60
6	20	10^9	1.10	1.00	10	1.3×10^9	9.10	1.30
7	20	10^9	1.10	1.00	30	7.1×10^9	10.0	9.50
8	20	10^9	1.10	5.00	10	1.3×10^9	14.0	1.20
9	80	10^8	0.93	0.10	10	1.3×10^8	10.6	0.94
10	80	10^8	0.93	0.10	30	1.3×10^8	10.4	0.99
11	80	10^8	0.93	0.10	100	1.6×10^9	11.2	16.0
12	80	10^8	0.93	0.10	300	5.1×10^9	11.0	12.0
13	80	10^9	1.80	1.00	10	8.1×10^8	20.3	1.90
14	80	10^9	1.80	1.00	30	8.2×10^8	19.8	2.10

Ongoing – What Dominates the Emission?

What does an observing instrument really see?

Hot plasma, the signature of impulsive heating?

Cooler plasma, happening to emit within the filter's wavelength sensitivity range?

The recent launch of SDO, with the Atmospheric Imaging Assembly (AIA), makes this a timely question

Equipped with filters sensitive to hot emission [94, 133 and 335 Å, covering Fe XVI to Fe XXIII (2.5 – 15 MK)]

These filters are also sensitive to cooler emission

What dominates the observed emission? The hot emission the filters are tuned to, or the cool emission at nearby wavelengths?

Ongoing – Emitting Ions of Relevance

Table 2: A summary of all the emitting ions, and those that the emit strong hot lines which certain of the filters have been centered on, in the wavelength sensitivity ranges of the instrument filters used in the present work. This summary was compiled using Chianti. The symbol ^{d} denotes a dielectronic satellite line.

Instrument / Filter (Å)	All Ions	Hot Ions
SDO-AIA / 94	Fe VIII, IX, X, XII, XV, XVII, XVIII, XIX XX, XXI, XIII, XXIII	Fe XVIII
SDO-AIA / 133	Fe VIII, IX, X, XI^{d}, XII, XV, XVII, XVIII XIX, XX, XXI, XXII, XXIII	Fe XX, XXIII
SDO-AIA / 195	Fe VIII, VIII^{d}, IX, X, XI, XI^{d}, XII, XIII XIII^{d}, XIV, XV, XV^{d}, XVII, XVIII, XIX, XX XXI, XXII, XXIII, XXIV, XXV	Fe XXIV
TRACE / 195	Fe VIII, IX, X, XI, XII, XIII, XIII^{d}, XIV XV, XVII, XVIII, XIX, XX, XXI, XXII, XXIII XXIV, XXV	Fe XXIV
SDO-AIA / 211	Fe VIII, VIII^{d}, IX, IX^{d}, X, XI, XI^{d}, XII XIII, XIII^{d}, XIV, XV, XVII, XVIII, XIX, XX XXI, XXII, XXIII, XXIV, XXV	Fe XIV
SDO-AIA / 335	Fe VI, VIII, IX, X, XI, XI^{d}, XII, XII^{d} XIII, XIII^{d}, XIV, XIV^{d}, XV, XV^{d}, XVI, XVI^{d} XVII, XVIII, XIX, XX, XXI, XXII, XXIII	Fe XVI, XVI^{d}
Hinode-EIS	Fe XI (192.830), XII (195.119), XV (284.163) XVI (262.976), XVII (254.347), XXIII (263.766) Ca XVII (192.820)	

Ongoing – Forward Modelling

Geometry:

Semi-circular loop of circular cross-section, oriented perpendicularly to the solar surface and aligned in the East – West direction

Instruments:

SDO-AIA (94, 133, 195, 211 and 335 Å), TRACE (195 Å) and Hinode-EIS (170 – 210 and 250 – 290 Å)

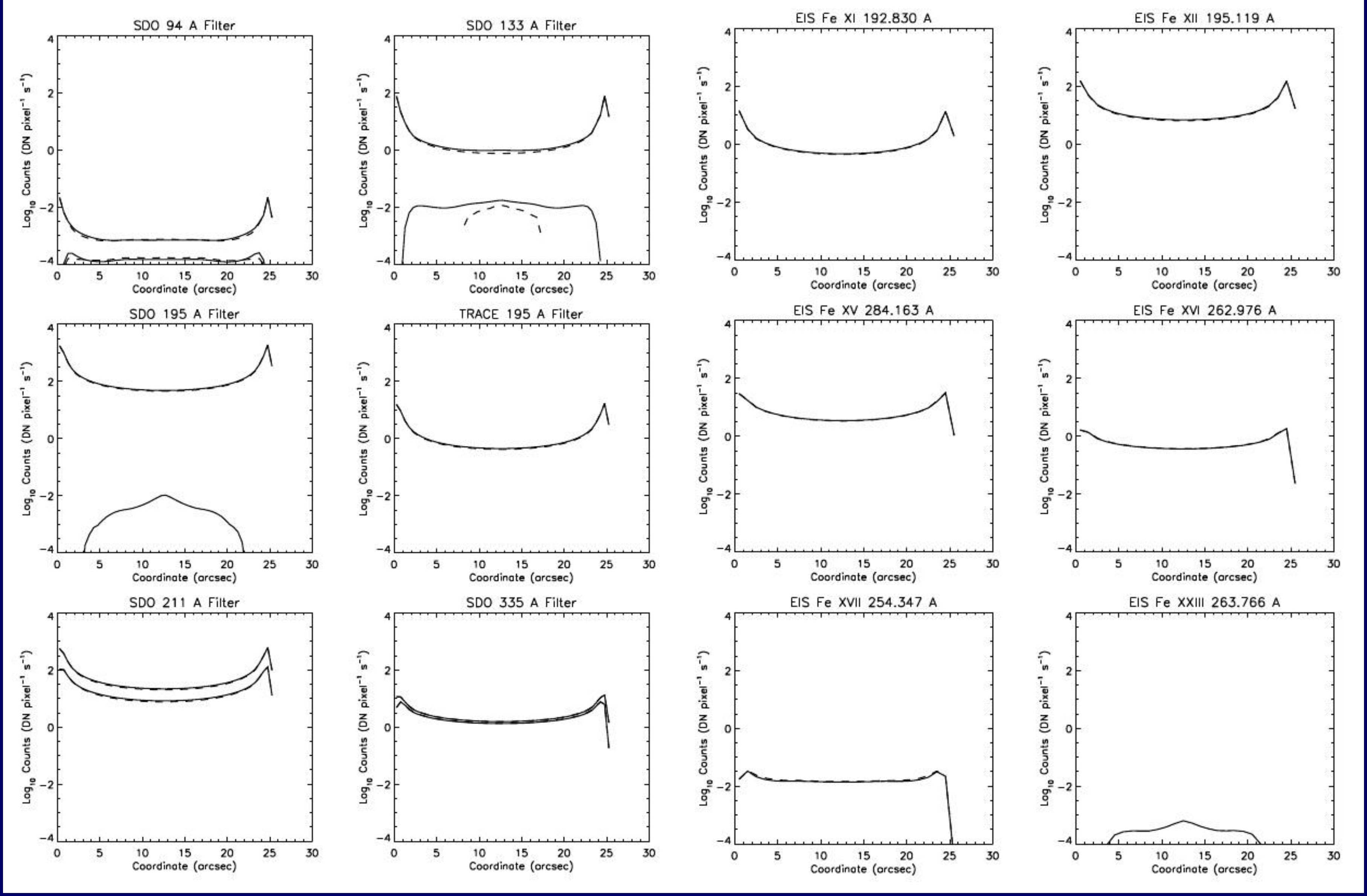
Emission:

Focus on iron (Fe) and calcium (Ca)

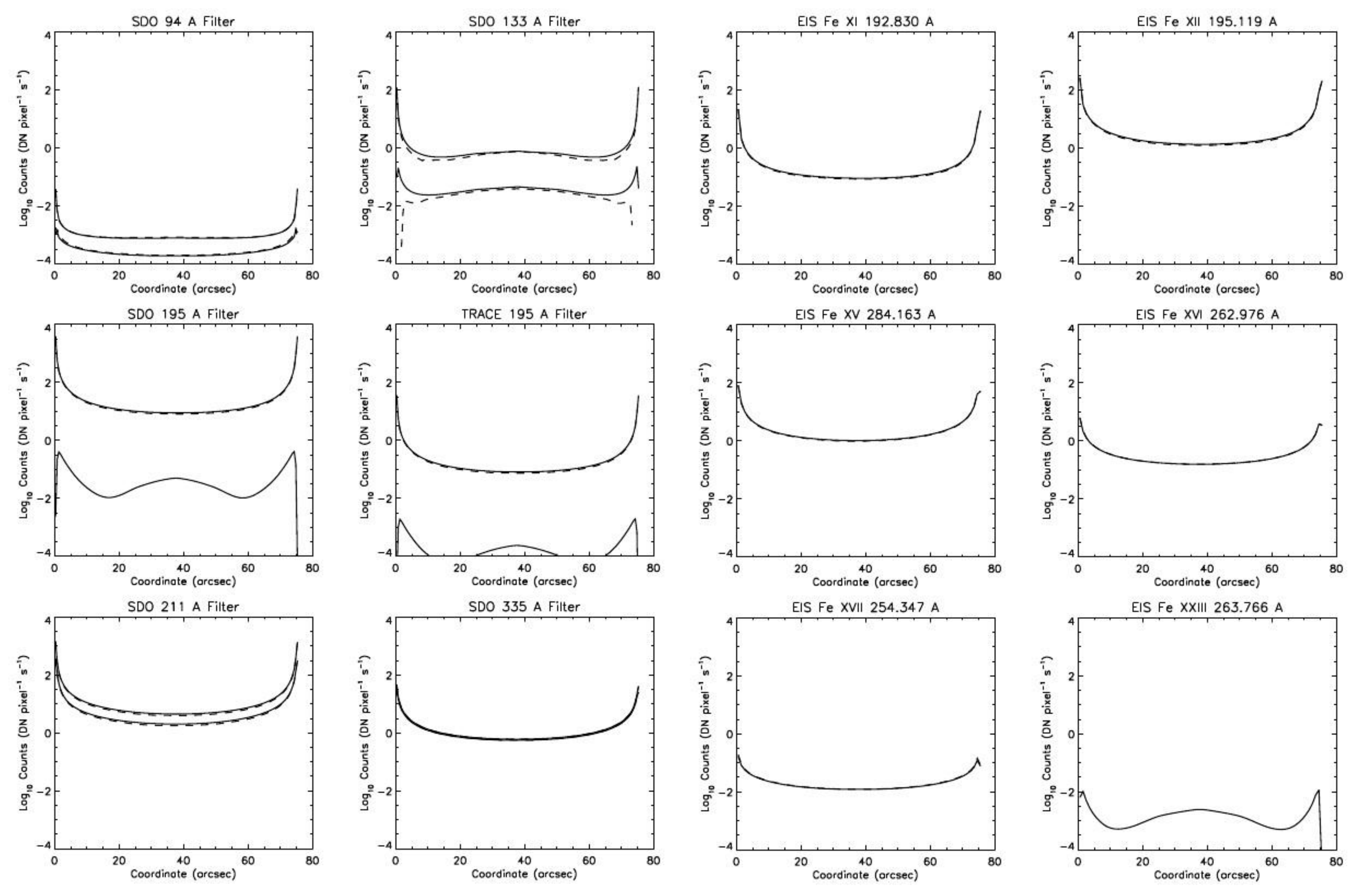
Computational demands:

3390 emission lines included in the forward modelling calculation for SDO-AIA 195 Å

Ongoing – Initial Results



Ongoing – Initial Results



Conclusions

The observation of emission in a hot filter is not sufficient evidence for the presence of hot plasma and therefore a signature of heating (impossible to disentangle hot and cooler components)

Spectroscopic observations are required for confirmation

Conversely, a lack of hot emission is not sufficient evidence to conclude that no heating is taking place

Non-equilibrium ionisation provides an entirely plausible scenario in which there are no emission signatures associated with the hottest plasma (agreement between the monolithic and multi-stranded cases)

In consequence, the multi-stranded case leads to the prediction that the observed emission is dominated by cooling strands in ionisation equilibrium

Good news for spectroscopic diagnostics!