Thermal Instabilities in Fully and Partially Ionized Prominence Plasmas

R. Soler (1), M. Goossens (1), S. Parenti (2), & J. L. Ballester (3)

[1] Centre for Plasma Astrophysics
K. U. Leuven (Belgium)

[2] Royal Observatory of Belgium

[3] Solar Physics Group
Universitat de les Illes Balears (Spain)

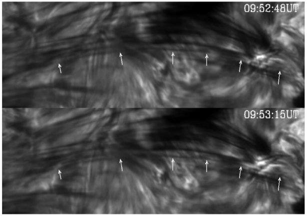
Workshop on Partially Ionized Plasmas in Astrophysics
Tenerife, 19 – 22 June 2012

Outline

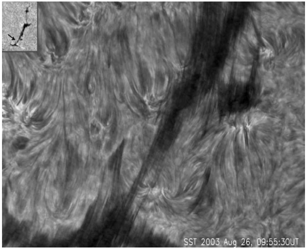
Filament threads: Observational aspects

- Quiescent and Active filaments are formed by a myriad of fine structures called threads Lin (2004); Okamoto et al. (2007)
- Threads are long (5 - 20 arc sec), thin (0.2 -0.4 arc sec) fine structures, partially or totally filled with low temperature plasma
- Observational evidence suggests that these fine structures are field aligned, outlining magnetic field tubes Engvold (1998); Lin (2004); Lin et al. (2005, 2007); Engvold (2007); Martin et al. (2008)

Lin et al. (2008)



Lin et al. (2008)

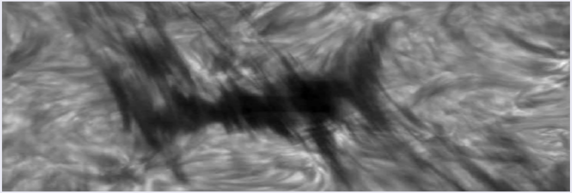


Lin et al. (2008)

Filament threads: Observational aspects

Flows and Lifetime

- Mass flows in filament threads routinely detected in $H\alpha$, UV and EUV observations, with speeds: 5 - 20 km/s (See Labrosse et al. 2010)
- Thread's lifetime is short. "Threads appear highly time variable since the absorbing parts come and go, possibly due to rapid heating and cooling of plasma. Lifetimes are in the range few - 20 minutes"(Lin et al. 2005; 2009)
- Suggested mechanisms to explain the short lifetimes: Thermal instability?; Kelvin - Helmholtz instability?, Rayleigh-Taylor Instability?, ionization-recombination processes?



(Movie from Y. Lin)

Thermal Instability of Solar Prominence Threads

- Is the short lifetime of threads caused by a Thermal Instability?

Thermal Instability

- Thermal or condensation modes have been investigated in homogeneous plasmas (Parker, 1953; Field, 1965; Heyvaerts, 1974; Carbonell et al. 2004)
- Carbonell et al. (2004): Study of the thermal mode in a homogeneous plasma with prominence, prominence-corona transition region (PCTR), and coronal conditions, considering parallel thermal conduction and optically thin radiative losses (Hildner, 1974)
- For long wavelengths, the thermal mode is unstable for PCTR temperatures since thermal conduction is not enough efficient to stabilize the thermal disturbance

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Thermal Instability of Solar Prominence Threads

- In inhomogeneous plasmas, thermal modes were studied in detail by Van der Linden et al. (1991),Van der Linden & Goossens (1991a, 1991b) and Van der Linden (1993)
- Van der Linden et al. (1991) pointed out the presence of a thermal continuum when non-adiabaticity is taken into account
- For temperatures between $10^4 - 10^7$ K, this thermal continuum can be unstable due to the destabilizing effect of radiative losses
- Furthermore, Van der Linden et al. (1991) and Van der Linden & Goossens (1991a) concluded that the inclusion of perpendicular conduction replaces the thermal continuum by a set of discrete modes
- Applying these results to prominence conditions, Van der Linden & Goossens (1991a) showed that the spatial scales of the most unstable modes are consistent with the size of prominence threads. Perpendicular thermal conduction could be responsible for the prominence fine structure
- Soler, Ballester & Goossens (2011) have followed a similar approach to investigate the thermal instability of an inhomogeneous thread model

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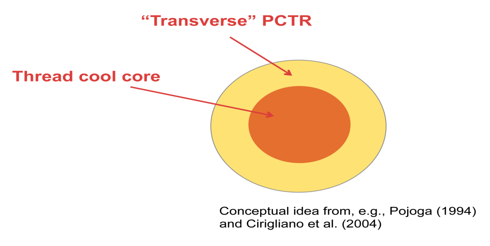
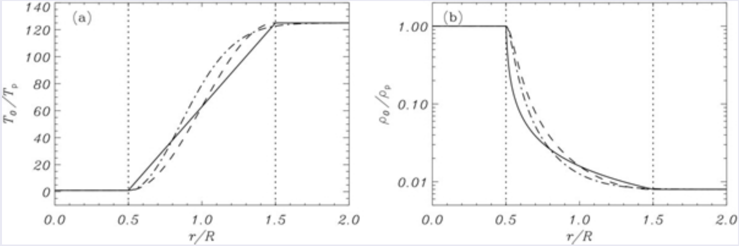
Thermal Instability in a Fully Ionized Filament Thread

Thread Model



Temperature and density profiles vs thread radius



Thermal Instability in a Fully Ionized Filament Thread

Parameters of Radiative Loss Functions

Table 1

Values in MKS Units of the Parameters in the Radiative Loss Function (Equation (8)) Corresponding to Several Temperature Regimes

Regime	Temperature Range	χ^*	α
Prominence-1.1	$T \leqslant 15\times10^3$ K	1.76×10^{-13}	7.4
Prominence-1.2	$T \leqslant 15\times10^3$ K	1.76×10^{-53}	17.4
Prominence-1.3	$T \leqslant 15\times10^3$ K	7.01×10^{-104}	30
PCTR-2	15×10^3 K $< T \leqslant 8\times10^4$ K	4.29×10^{10}	1.8
PCTR-3	8×10^4 K $< T \leqslant 3\times10^5$ K	2.86×10^{19}	0.0
PCTR-4	3×10^5 K $< T \leqslant 8\times10^5$ K	1.41×10^{33}	−2.5
Corona-5	$T > 8\times10^5$ K	1.97×10^{24}	−1.0
Klimchuk–Raymond-1	$T \leqslant 10^{4.97}$ K	3.91×10^{9}	2.0
Klimchuk–Raymond-2	$10^{4.97} < T \leqslant 10^{5.67}$ K	3.18×10^{24}	−1.0
Klimchuk–Raymond-3	$T > 10^{5.67}$ K	6.81×10^{18}	0.0

Notes. Prominence-1.1, PCTR-1, PCTR-2, PCTR-3, and Corona-5 regimes are parameterizations from Hildner (1974). Prominence-1.2 and Prominence-1.3 regimes are taken from Milne et al. (1979) and Rosner et al. (1978), respectively. The three Prominence regimes represent different plasma optical thicknesses, Prominence-1.1 corresponding to optically thin plasma, while Prominence-1.2 and Prominence-1.3 are for optically thick and very thick plasmas, respectively. The three Klimchuk–Raymond regimes are adapted from Klimchuk & Cargill (2001), where we have only taken into account the range of temperatures considered in our equilibrium.

Thermal Instability in a Fully Ionized Filament Thread

- MHD equations for non-adiabatic and resistive plasmas
- Parallel and perpendicular conduction considered
- Hildner and Klimchuk-Raymond radiative losses
- Linear perturbations proportional to $exp(st + im\varphi - ik_z z)$
- s: growth rate; m: azimuthal wavenumber; k_z: longitudinal wavenumber

Normalized Thermal continuum vs r/R (Hildner function; $\kappa_\perp = \eta = 0$)

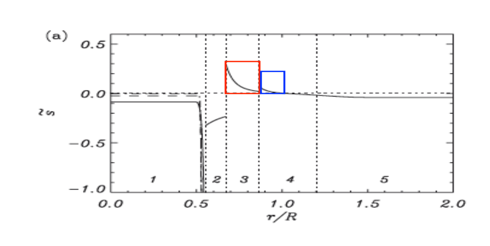


Figure: Growth rate > 0 in PCTR 3 and part of PCTR 4 ($k_z R = 10^{-2}$)

Thermal Instability in a Fully Ionized Filament Thread

Effect of perpendicular thermal conduction. $\eta = 0$

- Thermal continuum replaced by a set of discrete modes

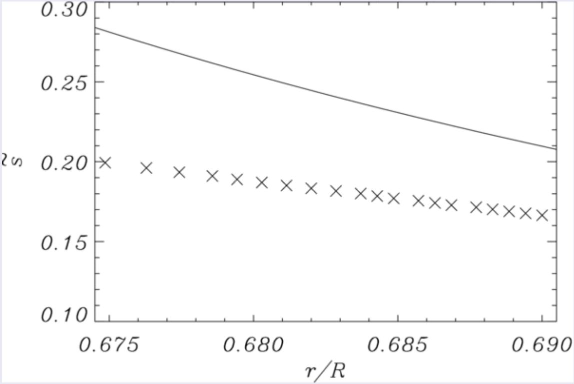
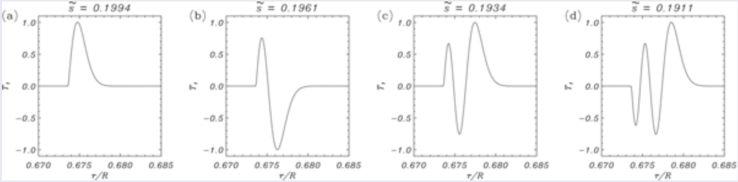


Figure: Normalized growth rate of 20 most unstable modes. The solid line represents the thermal continuum in absence of perpendicular thermal conduction

Thermal Instability in a Fully Ionized Filament Thread

Temperature perturbations (m = 0; Four most unstable modes. $\kappa_\perp \neq 0; \eta = 0$)



Conclusions

- Presence of spatial temperature fluctuations within the transverse PCTR
- Simultaneous plasma heating and cooling in the PCTR
- Plasma cooling and heating may cause the maximum of the emission to fall outside the bandpass of the filter, and so the thread would fade with time and eventually disappear from $H\alpha$ images

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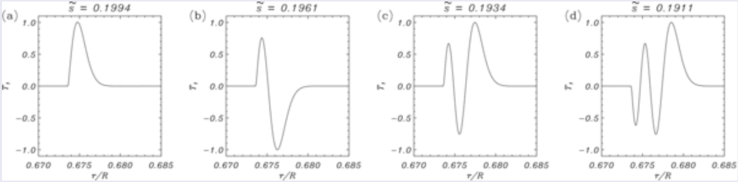

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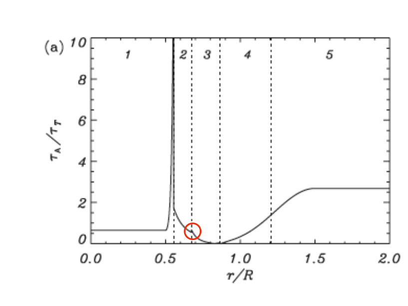
$\kappa_{\parallel} \neq 0$, $\kappa_{\perp} = 0$, $\eta \neq 0$. Ratio of the Alfvén timescale to thermal continuum timescale



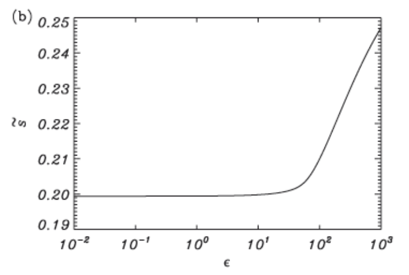
- When $\tau_a << \tau_t$, magnetic diffusion replaces thermal continuum by a discrete set of modes. In the opposite case, magnetic diffusion has no effect (Ireland et al. 1992)
- In the most unstable part of the continuum (beginning of PCTR3), the ratio ~ 1. Our case is between the above limit cases, but no discrete modes appear

Thermal Instability in a Fully Ionized Filament Thread

$\kappa_{\|} \neq 0$, $\kappa_{\perp} \neq 0$, $\eta \neq 0$

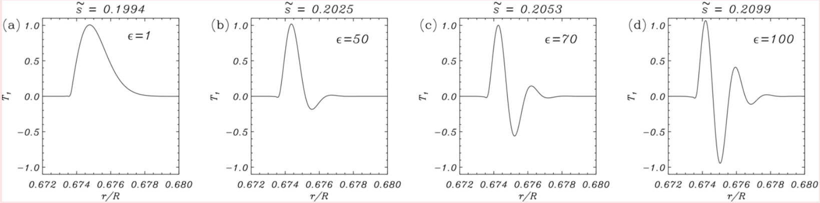
- Enhanced diffusivity: η replaced by $\epsilon\eta$
- For $\epsilon \leq 50$, the growth rate is the same as for $\eta = 0$
- For $\epsilon > 50$, the growth rate increases and magnetic diffusion governs the behaviour of the solution

Normalized growth rate of the most unstable mode vs ϵ



Thermal Instability in a Fully Ionized Filament Thread

Temperature perturbations most unstable mode vs r/R and for different ϵ



- For $\epsilon = 1$, same growth rate as for $\eta = 0$
- For $\epsilon = 1$, eigenfunction has the same shape as for $\eta = 0$
- We would need unrealistic values of η for the growth rate to be affected by diffusion

Thermal Instability in a Fully Ionized Filament Thread

Parametric study

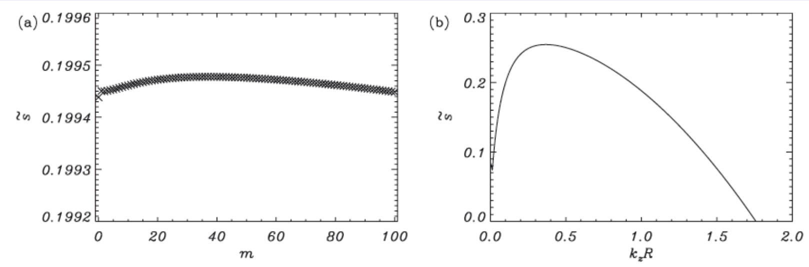


Figure: Normalized growth rate of the most unstable mode vs (a) the azimuthal wavenumber; (b) the longitudinal wavenumber

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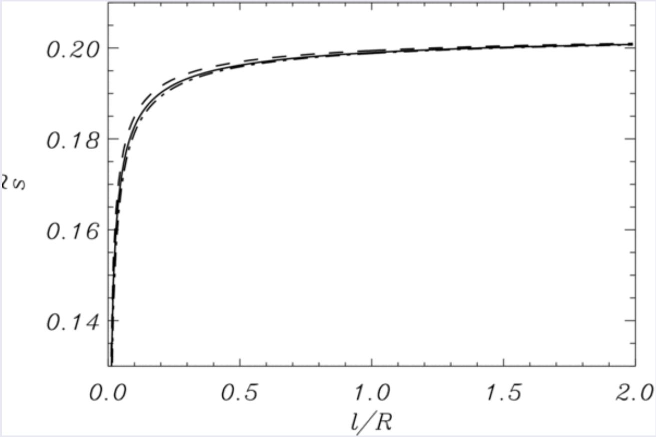

Figure: Normalized growth rate of the most unstable mode vs thickness of transition layer. m = 0

Thermal Instability in a Fully Ionized Filament Thread

Thermal instability time scale (H & KR radiative losses)

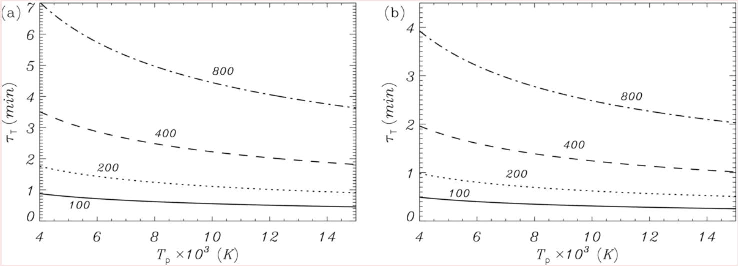

Figure: Thermal instability time scale (most unstable mode) vs temperature of thread core and different thread radius. H & KR radiative losses

- Cool and wide threads are more thermally stable

Thermal Instability in a Fully Ionized Filament Thread

Conclusions

- Unstable thermal modes appear in the PCTR of prominence threads
- These unstable discrete modes appear due to the effect of the perpendicular thermal conduction
- Only the linear stage of the thermal instability has been studied
- The growth rate of the linear phase provides with a timescale on which the effect of thermal instability should be observable
- Instability time scale $\sim$ minutes!
- Instability time scale of the same order as observed lifetime of threads in $H\alpha$ images
- Thermal instability may play a relevant role in the dynamics and stability of prominence fine structures

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Thermal Instability in Partially Ionized Prominence Plasmas

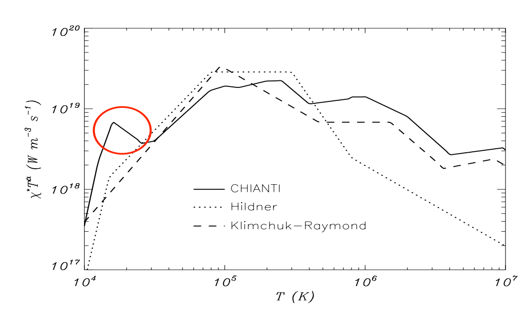
Radiative loss functions

- An accurate description of the radiative loss function is crucial to ascertain the stability of thermal modes
- The determination of the radiative loss function in prominence plasmas, depending on the values of temperature and density, is a difficult task
- Semi-empirical parametrizations have been used: Hildner (1974); Klimchuk-Raymond (Klimchuk & Cargill, 2001)
- The shape of the loss function depends on the accuracy of the atomic model used, the atomic processes included, the ionization equilibrium and element abundance assumed
- Recent loss functions: CHIANTI V7; Schure et al. (2009)

Thermal Instability in Partially Ionized Prominence Plasmas

- Recently, Soler, Ballester & Parenti (2012) have used radiative losses derived from CHIANTI V7 (Landi et al. 2012) database, to re-analyze thermal instability

CHIANTI V7 loss function



- Region of instability appears at low temperatures ($1.58 \times 10^4 - 3.16 \times 10^4$ K)

Thermal Instability in Partially Ionized Prominence Plasmas

- Unbounded prominence plasma made of partially ionized hydrogen (ions, electrons, neutrals) with uniform $\vec{B} = B\hat{z}$
- MHD equations for non-adiabatic and resistive partially ionized plasmas. Parallel ($\kappa_e + \kappa_n$) and perpendicular (κ_n) conduction considered

Growth rate vs temperature (No conduction, No Cowling's diffusion)

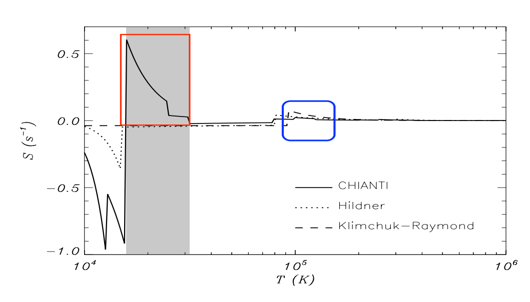


Figure: Approximate thermal mode growth rate vs temperature for Hildner, Klimchuk-Raymond and Chianti loss functions

Thermal Instability in Partially Ionised Filament Plasmas

Numerical Results

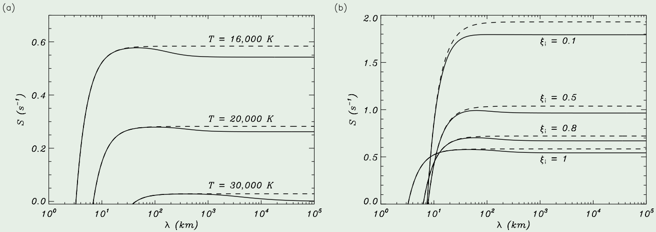


Figure: Numerical growth rate (solid) and approximation (dashed) for fully (left) and partially ionized (right) plasmas vs wavelength for CHIANTI loss function. $T = 16000\ K$ in the right panel

Conclusions and Closing remark

Conclusions

- Thermal instability can take place in prominences at lower temperatures than those predicted by other loss functions
- Instability time scale very short ($\sim s$). Why?
- Stabilizing effect coming from thermal conduction by neutrals increases the critical wavelength
- In a transverse non-homogeneous filament thread, Thermal Instabilities in the PCTR and in the cool core should appear

Closing remark

- Thermal and MHD Instabilities seem to play a key role in prominence dynamics. For this reason: Instabilities in fully and partially ionized prominence plasmas need to be investigated using analytical and numerical tools, paying attention to the non-linear phase

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References

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