Constraining stellar CME occurrence with optical spectroscopy – updated results for M dwarfs

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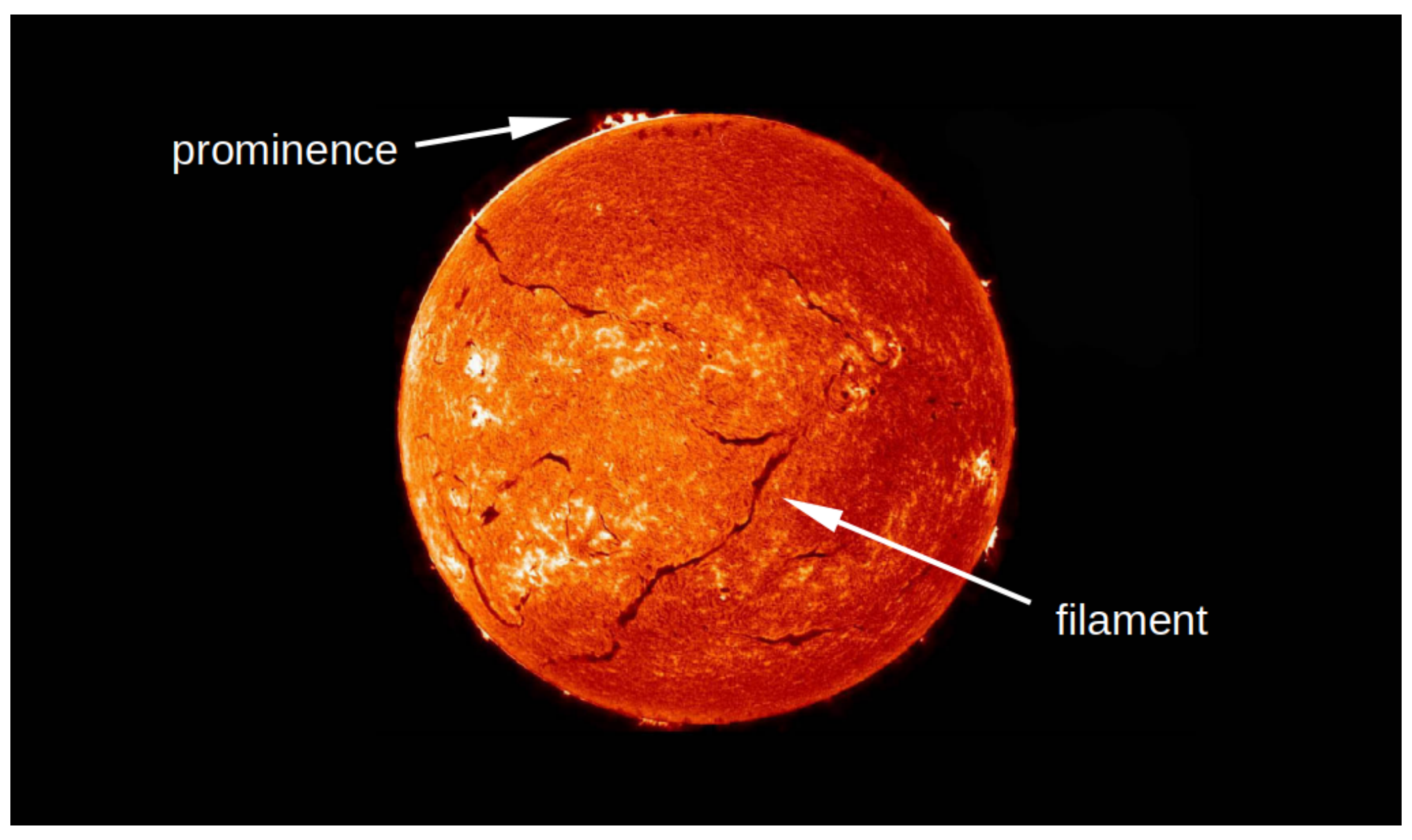
Abstract

Optical spectroscopic observations sometimes show asymmetrically broadened wings and/or transient extra-emissions in chromospheric lines during or shortly after flares. Such events appear most commonly on active M dwarfs. These signatures could be due to prominence eruptions, which are closely related to CMEs on the Sun. Here we present an updated semi-empirical model which combines predictions of intrinsic stellar CME rates with radiative transfer calculations in the Balmer lines. Although Balmer signatures of (eruptive) prominences are typically dominated by scattering of the incident radiation on the Sun, we find that for M dwarfs the contribution of thermal emission should not be neglected. Its inclusion can lead to modified visibility compared to our previous study which assumed only scattering. Our updated model also predicts that filaments (i.e. prominences located in front of the stellar disk) can appear in emission for a wide range of plasma parameters on M dwarfs, in contrast to the Sun. This finding is consistent with existing observations of M dwarfs, which show typically blue asymmetries/blue-shifted line components in emission, but reports of absorption signatures are uncommon.

1. Radiative transfer in Balmer lines

Prominences are commonly observed in Hα on the Sun. They appear bright above the limb, but dark if viewed against the solar disk, in which case they are called filaments. Their eruptions can lead to CMEs, in which the erupting prominence plasma is embedded in the CME core.



Solar Hα image with prominences and filaments. Image credit: NOAA/SEL/USAF

The emergent intensity of a 1D prominence slab can be computed from a simplified solution to the general radiative transfer equation (assuming constant S through the slab and direction μ=1)

$$I = I_0 \exp(-\tau) + S[1-\exp(-\tau)], \qquad (1)$$

where I_0 is the incident radiation from the opposite side of the slab, S the source function of the prominence, and τ the optical thickness [e.g. 1, 2]. If the prominence is located in front of the stellar disk (i.e., filament geometry), then I_0=I_* (intensity of the stellar disk); if it is located above the limb (i.e., prominence geometry), then I_0=0.

2. Source function

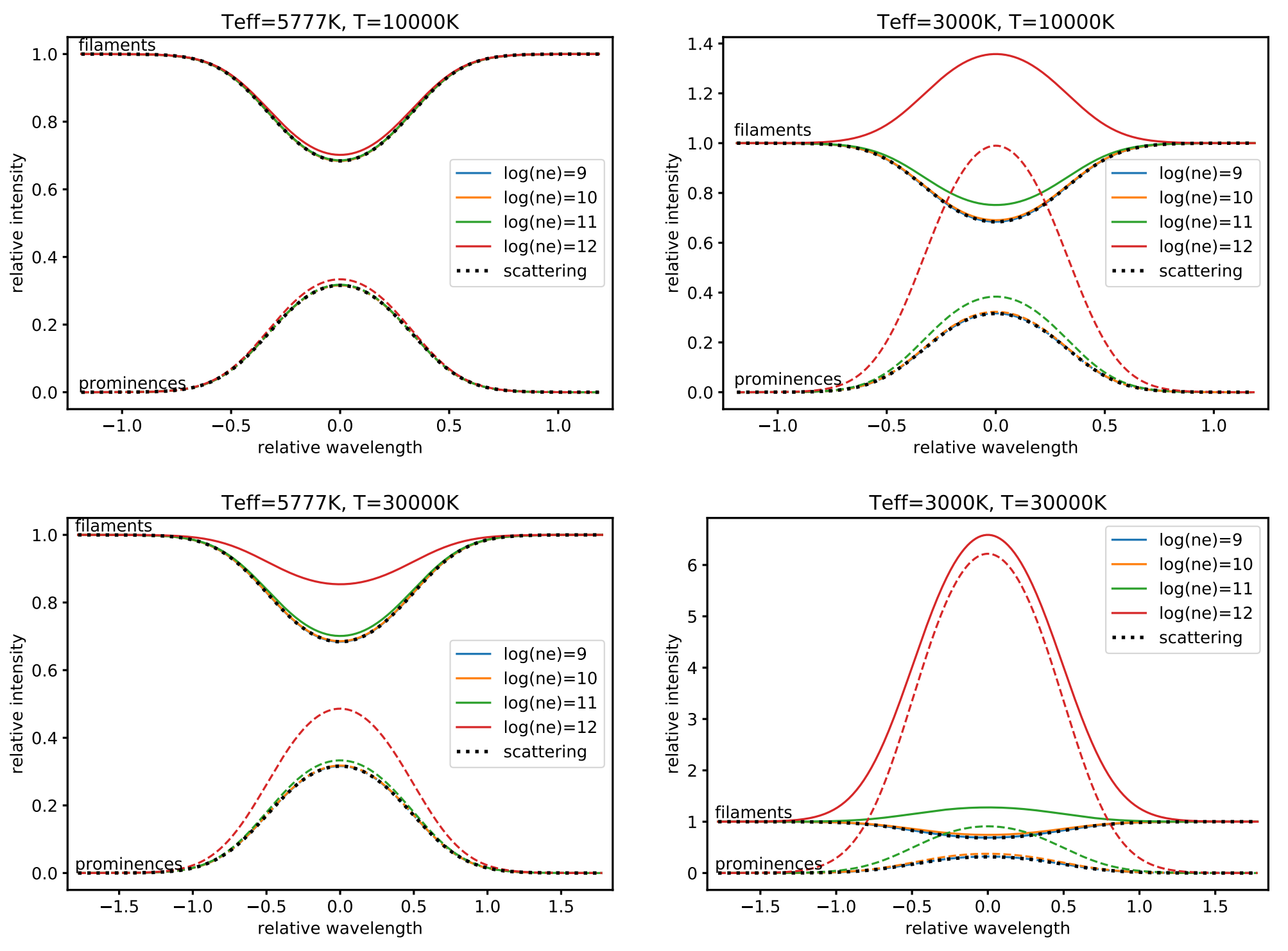
For S, we previously [5] assumed it is dominated by scattering of stellar light, as in solar prominences. Now we implement a so-called "generalized source function" derived from a simple 2-level atom model [cf. 1]

$$S = (1-\epsilon)WI_* + \epsilon B(T), \qquad (2)$$

which includes the contributions of scattering as before (WI_*, where $W \leq 0.5$ is the geometrical dilution factor which depends on the height of the prominence above the stellar surface), as well as the thermal emission ($B(T)$ is the Planck function at the prominence temperature T). The parameter ϵ represents the relative importance of collisional and radiative transitions and depends on temperature T and electron density n_e [1].

3. Effects of thermal emissionn

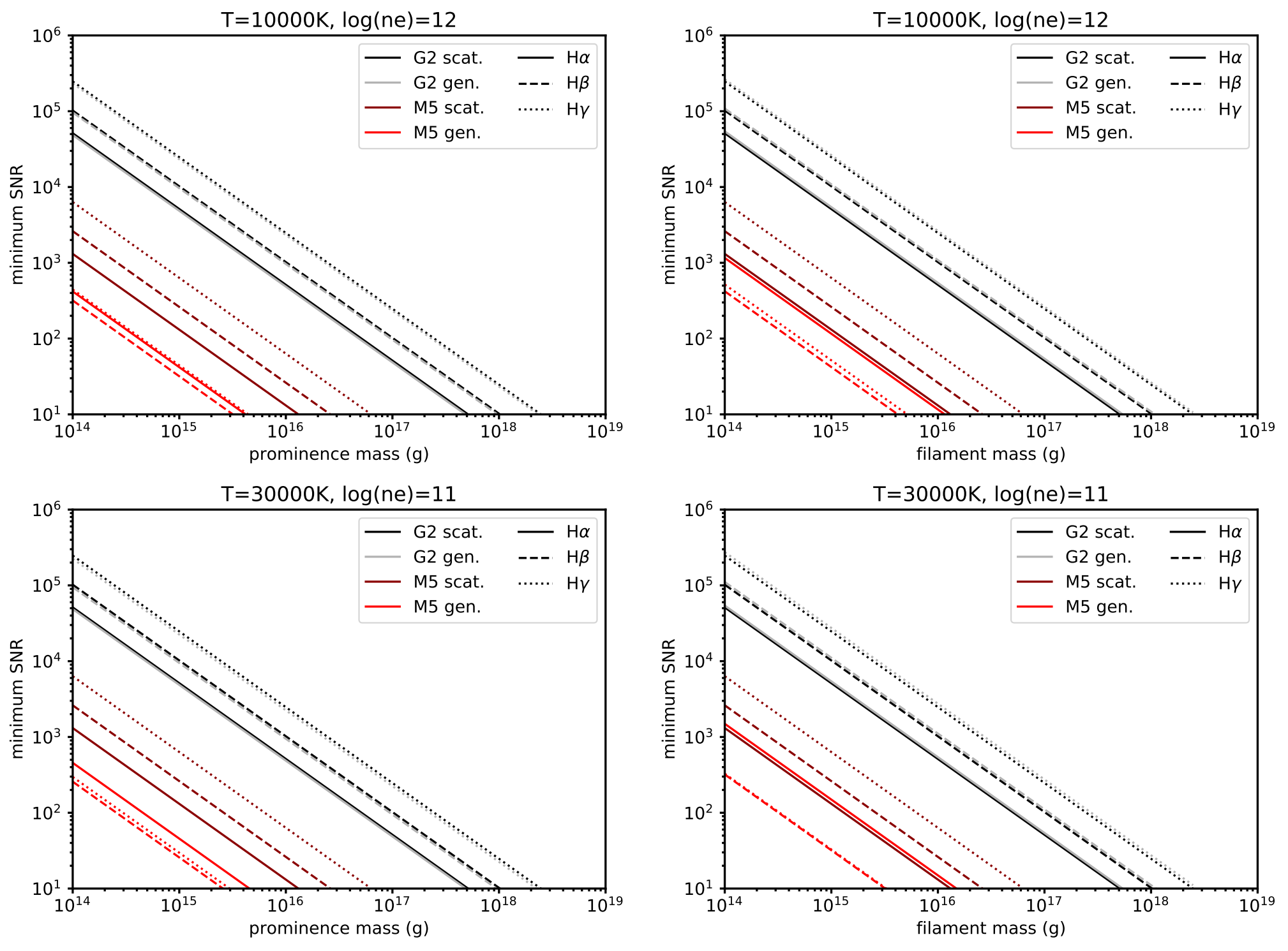
We explore here the effects of the generalized source function (Eq. 2) on the emergent prominence Hα intensities for Sun-like stars and M dwarfs within plausible ranges of prominence plasma parameters, revealing important differences. First, we find that for solar-type stars (left column) the contribution of thermal emission has an (almost) negligible effect on the emergent intensities, especially for the typical solar parameter ranges of $T \lesssim 10000$ K and $n_e \sim 10^9 - 10^{11}$ g cm^{-3} [2]. However, for M dwarfs (right column) even the upper range of solar plasma parameters already affects the intensities. Prominence intensities are boosted, whereas filament signatures are reduced until they even switch to emission for increasing n_e and/or T above typical solar values.



Although Eq. 2 provides mainly qualitative results, we confirm this behavior with dedicated radiative transfer modeling using an adapted solar NLTE code applied to an M dwarf star [3, 4]. These aspects leads to the conclusion that our previous approach likely underestimated the prominence observability for M dwarfs, and that absorption signatures from filaments were overestimated. Moreover, even in the case of an Hα absorption signature in the filament case, some higher Balmer lines may simultaneously be in emission or undetectable, because higher lines are already affected at lower values of n_e and T.

4. Minimum signal-to-noise ratio

As the spectral line peak of an erupting prominence relative to the stellar pre-event spectrum must exceed the SNR of the data, we can estimate the minimum SNR to detect such events. Following our previous approach [5], we demonstrate the effects of Eq. 2 below. We adopt W=0.5, $\mathcal{N}_{\rm H}$=10^{20} cm^{-2}, $\tau_0({\rm H}\alpha)$=5 and show two different T and n_e combinations for spectral types G2 and M5 and the first three Balmer lines, compared with pure scattering. The left column shows the effect for prominence geometry, the right one for filaments. One can see that the results for Sun-like stars are barely affected, whereas for an M5 star the required SNR is reduced in most cases, and the higher Balmer lines become more promising. Note that the filaments appear in emission on the M5 star in all of the shown cases.



5. Summary and outlook

- ➤ Depending on the plasma parameters, the contribution of thermal emission can have a pronounced effect on the detection of stellar filament/prominence eruptions on M dwarfs.
- ➤ In the next step, combining the updated radiative transfer model with intrinsic CME rate estimates [6] will improve previous detectability estimates of Odert et al. [5] for M dwarfs.
- ➤ However, more detailed comparison with dedicated NLTE modeling is necessary to better constrain the parameter space in which the simple Eq. 2 provides a reliable approximation.

References

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