Constraining stellar CME occurrence with optical spectroscopy

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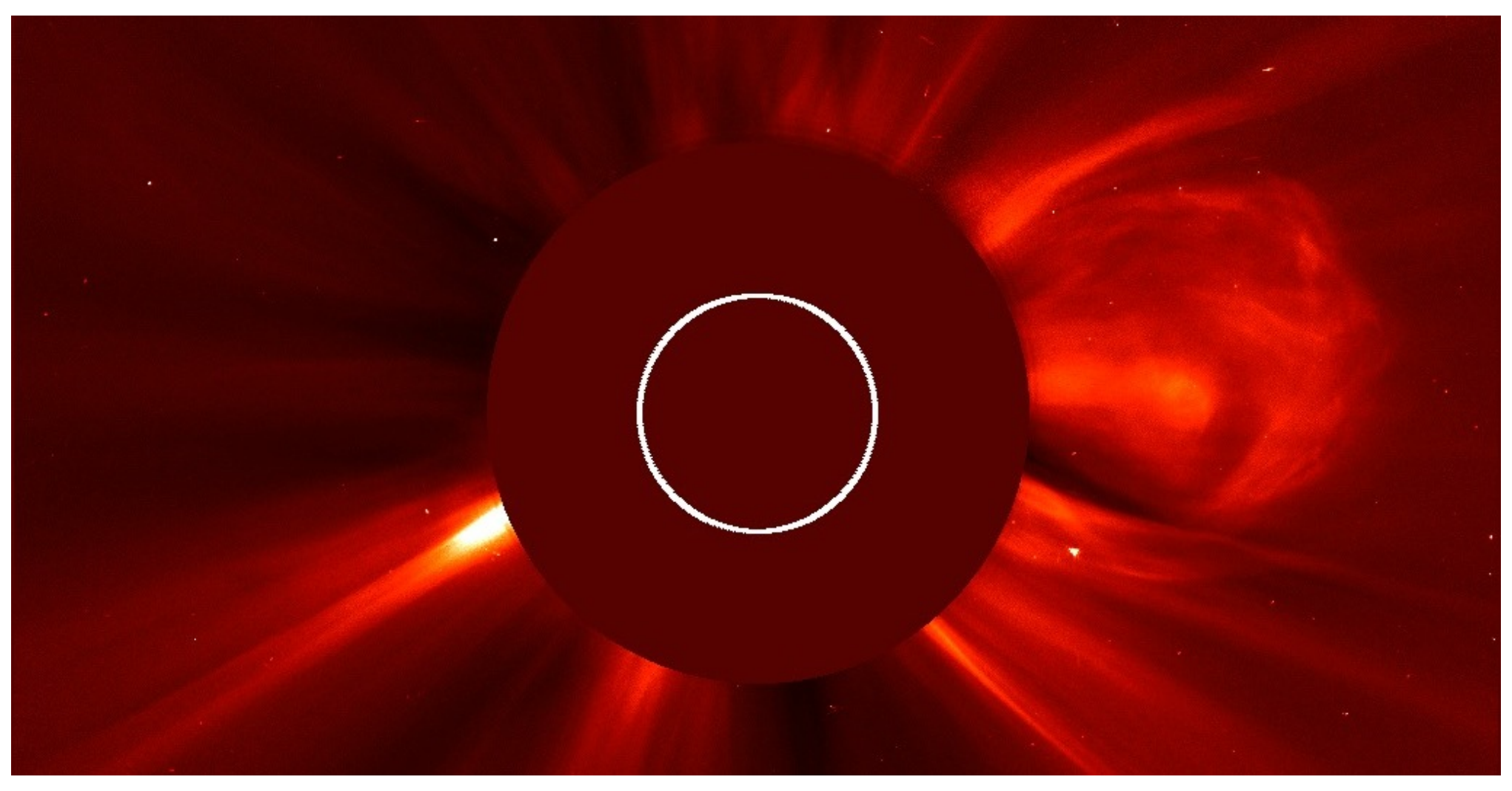
Abstract

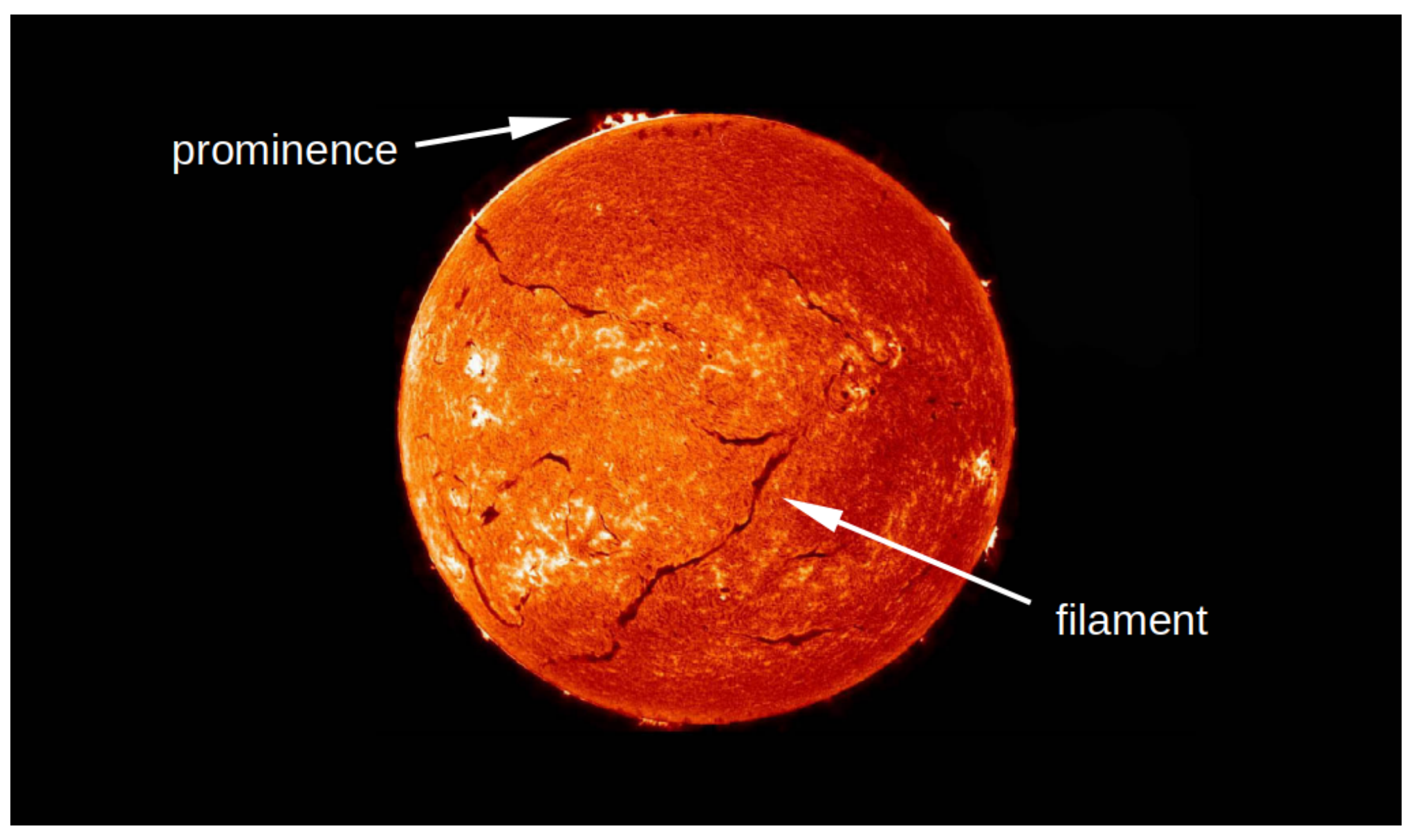
Our knowledge on coronal mass ejections (CMEs) on stars other than the Sun is still sparse. Spectroscopic observations in the optical sometimes show asymmetrically broadened wings and/or transient extra-emissions in chromospheric lines during or shortly after flare events. These may be interpreted as signatures of prominence eruptions, which are closely related to CMEs on the Sun. Dedicated searches for these signatures have, however, mostly yielded non-detections. Here we present a semi-empirical model which combines predictions of intrinsic stellar CME rates with simple radiative transfer calculations in the Balmer lines. We find that typical observations have most likely been too short and/or they had a too low signal-to-noise ratio to detect CMEs. We predict the minimum observing time needed to detect CMEs in the Balmer lines for stars with different spectral types and activity levels.



Solar CME event. Image credit: NASA

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 case the prominence plasma forms the core of the CME.



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

The emergent intensity of a 1D prominence slab at a certain wavelength can be written as

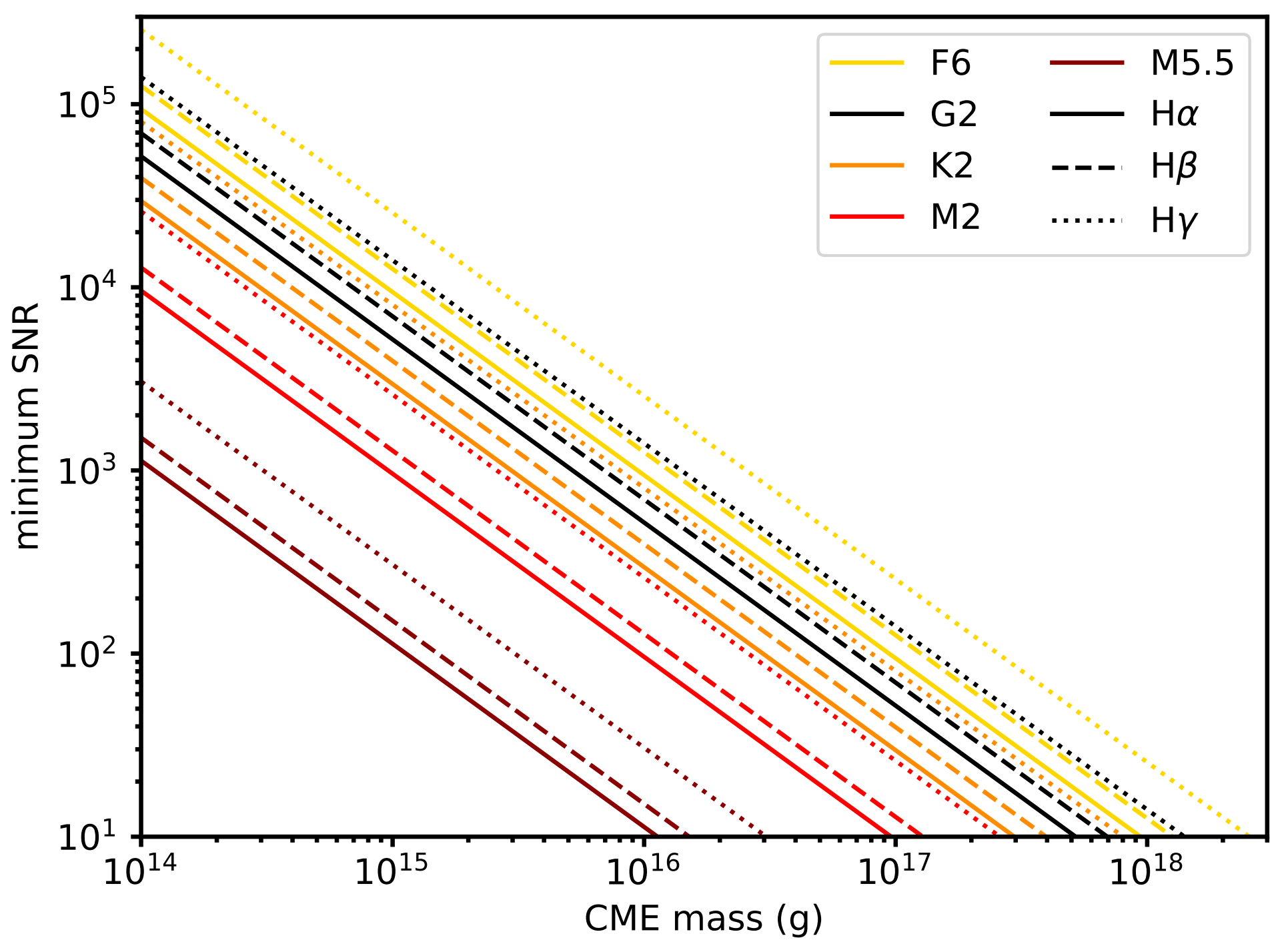
$$I = I_0 \exp(-\tau) + S[1 - \exp(-\tau)] \qquad (1)$$

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]. This is a simplified solution to the general radiative transfer equation by assuming constant S through the slab and direction μ=1.

If the prominence is located in front of the stellar disk (i.e., filament geometry), then I_0=I_*, i.e. the intensity of the stellar disk; if it is located above the limb (i.e., prominence geometry), then I_0=0. For S, we assume it is dominated by scattering of stellar light (as in solar prominences), which gives S=WI_*, where $W\leq0.5$ is the geometrical dilution factor (depends on the height of the prominence above the surface and the stellar radius [1]).

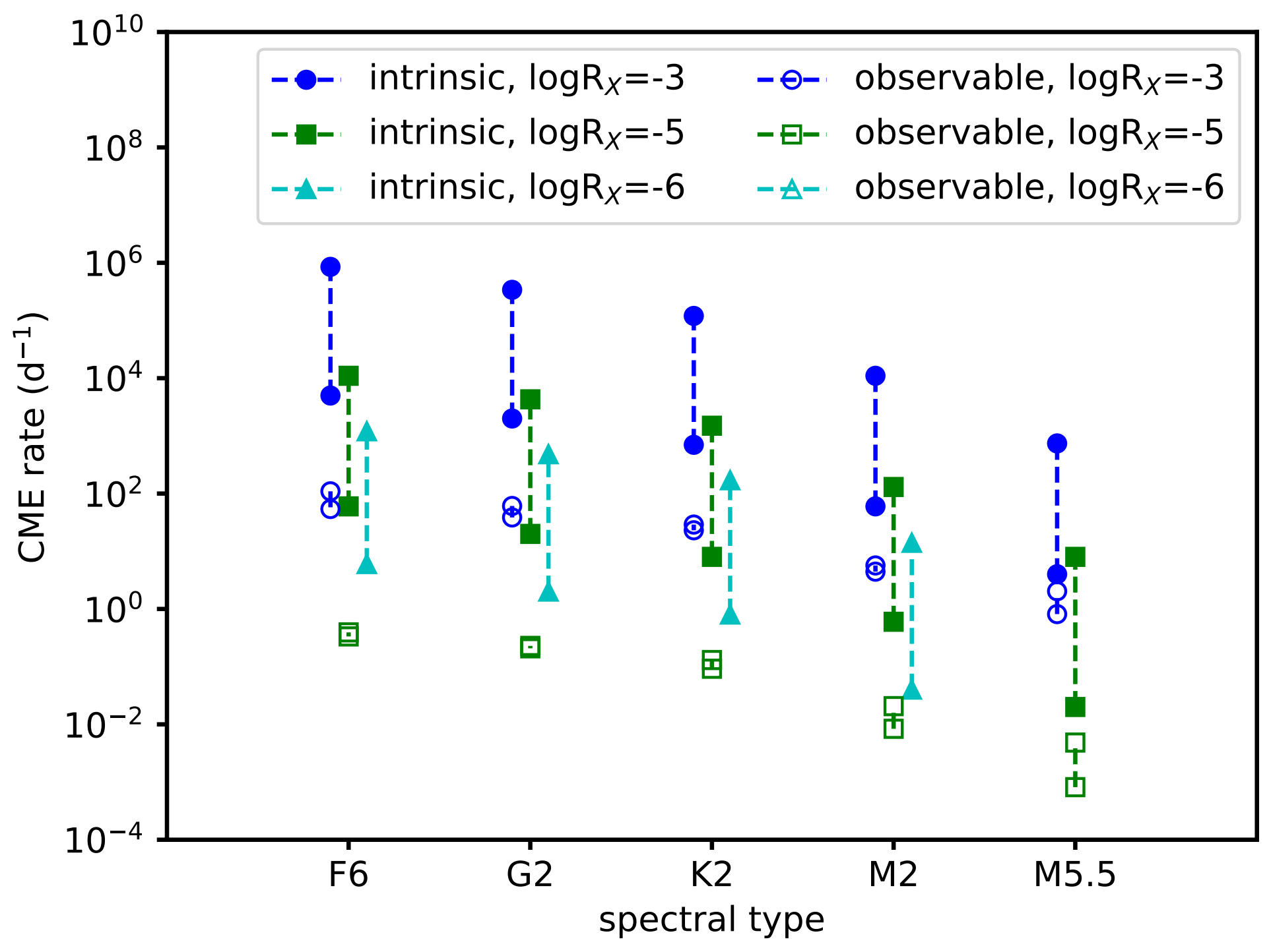
2. Minimum signal-to-noise ratio

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. We thus evaluate Eq. 1 in the line center and calculate the total star+prominence flux by summing their relative contributions. We found that $SNR_{\rm min}$ depends on W, τ_0 (line center value), and the area ratio of prominence to stellar disk A/A_* [3]. We use the relation M=$m_{\rm H}\mathcal{N}_{\rm H}A$ to connect prominence area A with its mass M, where $m_{\rm H}$ is the hydrogen mass and $\mathcal{N}_{\rm H}$ the column density. Below we show the results for W=0.5, $\mathcal{N}_{\rm H}$=$10^{20}\,{\rm cm}^{-2}$, τ_0(Hα)=10 for different stellar spectral types and Balmer lines. Smaller (larger) $\mathcal{N}_{\rm H}, \tau_0$ raise (reduce) $SNR_{\rm min}$ for a given M; reducing W (i.e., increasing the prominence height) increases (decreases) $SNR_{\rm min}$ for prominence (filament) geometry (W=0.5 gives equal $SNR_{\rm min}$ for both cases).



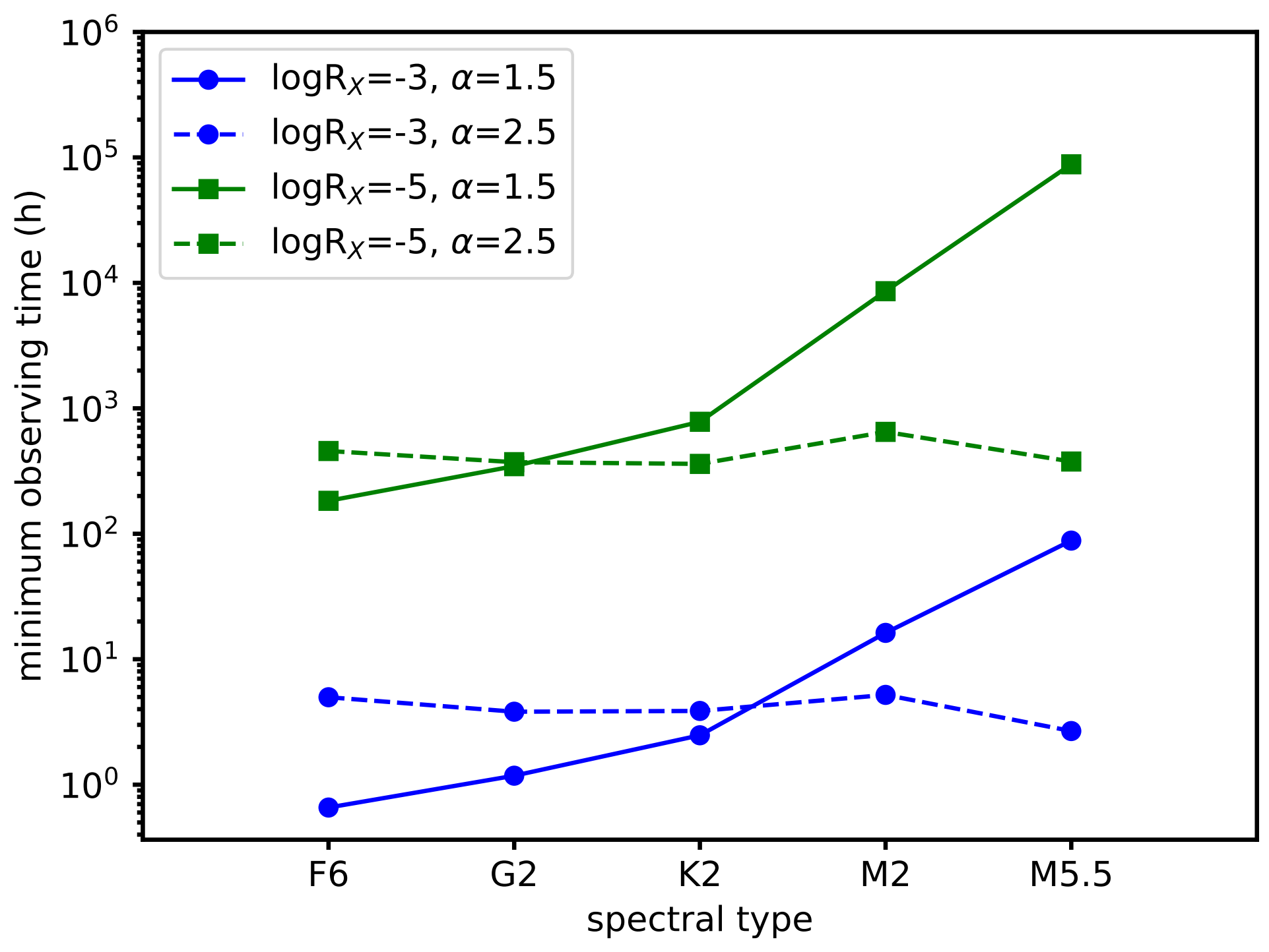
3. Intrinsic vs. observable CME rates

The detectability of CMEs in Balmer lines depends on 1) the emergent line intensities, 2) geometrical limitations, and 3) evolutionary effects during propagation. To estimate the maximum detectable CME rate, we calculate their maximum possible Balmer signals (i.e., assuming the CME consists of neutral hydrogen only), correct for undetectable events due to viewing geometry (statistically via distributions of line-of-sight velocities $v_{\rm los}$ and the maximum duration of absorption signals based on random directions of ejection), and propagation effects ("effective" W by accounting for increasing CME height during propagation). The intrinsic CME rates are estimated with an empirical model [4] based on stellar X-ray luminosity and the power law index α of the stellar flare rate distribution. The example figure shows the comparison of intrinsic and maximum observable CME rates (assumed parameters: $\mathcal{N}_{\rm H}$=$10^{20}\,{\rm cm}^{-2}$, τ_0(Hα)=10, $v_{\rm los}\geq100\,{\rm km\,s}^{-1}$, SNR=100, $t_{\rm exp}$=5 min) depending on stellar spectral type and activity level ($\log R_{\rm X} = \log(L_{\rm X}/L_{\rm bol})$); dashed lines display the flare power law index range of α=$1.5\ldots2.5$ [3].



4. Minimum observing time

Modeling the occurrence rate of CMEs as a Poisson process, we can infer the minimum observing time needed to detect at least one CME in Balmer lines with 95% probability. The example figure below adopts the same parameters as before. Additionally, dependencies on all relevant observational (SNR, $v_{\rm los}$, exposure time, Balmer line) and CME parameters (speed, column density) are shown in the appendix of Odert et al. [3].



5. Summary

- Observations of CMEs in Balmer lines is favorable for M dwarfs, as detection is feasible with lower SNR spectra, and the fraction of observable relative to intrinsic CME rates is higher.
- CMEs will likely only be detectable around the most active stars with this method, as the expected minimum observing times become prohibitively long for stars with lower activity levels.

References

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