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Understanding the universal heating mechanism of solar and stellar atmospheres

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One of the outstanding mysteries of the solar and stellar plasmas is why these stars commonly host extremely hot outer atmospheres, including the corona with a temperature of over 1 million Kelvin and the chromosphere of about 10,000 Kelvin. It is evident that these plasmas are magnetically heated, which is explained by the two representative scenarios: the wave heating model, in which magnetohydrodynamic waves transport kinetic energy from the stellar surface upward, and the nanoflare model, in which dissipation of magnetic energy occurs at localized current sheets. To investigate whether the heating mechanism is common between the Sun and Sun-like stars, we examined the scaling relations of magnetic flux vs. irradiances over a broad spectral range from X-rays to radio waves [1].

Using the long-term Sun-as-a-star observation data over the last 10 years, we created scatter plots of magnetic flux and irradiances of different spectral lines, which are sensitive to the plasmas with the formation temperatures from log(T [K]) = 6-7 (corona) to ~3.8 (chromosphere). Figure 1 shows the double logarithmic scatter plots, in which the colored dots represent the solar data. In each panel, we fitted a straight line to the data points. The obtained scaling laws were then compared with the observational data of G-type main-sequence stars of a variety of activity level with ages from 50 Myr to 4.5 Gyr.

It was found that the stellar data points are located at the extensions of solar power laws, even though the exponents very for different formation temperatures. This striking consistency indicates that the plasma heating mechanism is universal to the Sun and Sun-like stars, regardless of stellar ages and activity levels.

The above results further motivated us to model the spectra of Sun-like stars, specifically of the ultraviolet (UV) and X-ray range [2]. By measuring the power-law scaling between the irradiance and magnetic flux for each wavelength bin of UV/X-ray, we reconstructed the spectra for the active Sun-like stars. As shown in Figure 2, we confirmed that the reconstructed spectra are in good agreement with the actual observations, indicating that our empirical reconstructions can be used for, e.g., input to the photochemical calculation of exoplanetary atmospheres, which may provide clue to understanding the habitability on close-in exoplanets around the active stars.

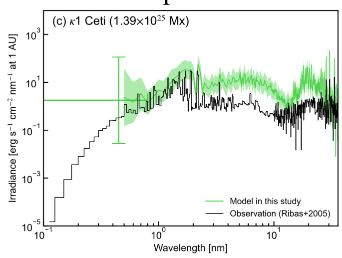

Figure 2: Comparison between the reconstructed spectrum (green) and actual stellar data (black) for the active young Sun-like star κ[1] Ceti (600 Myr). Figure adopted from [2].

References
[1] S. Toriumi & V. S. Airapetian, The Astrophysical Journal, 927, 179 (2022)
[2] K. Namekata, S. Toriumi, V. S. Airapetian, et al., The Astrophysical Journal, 945, 147 (2023)

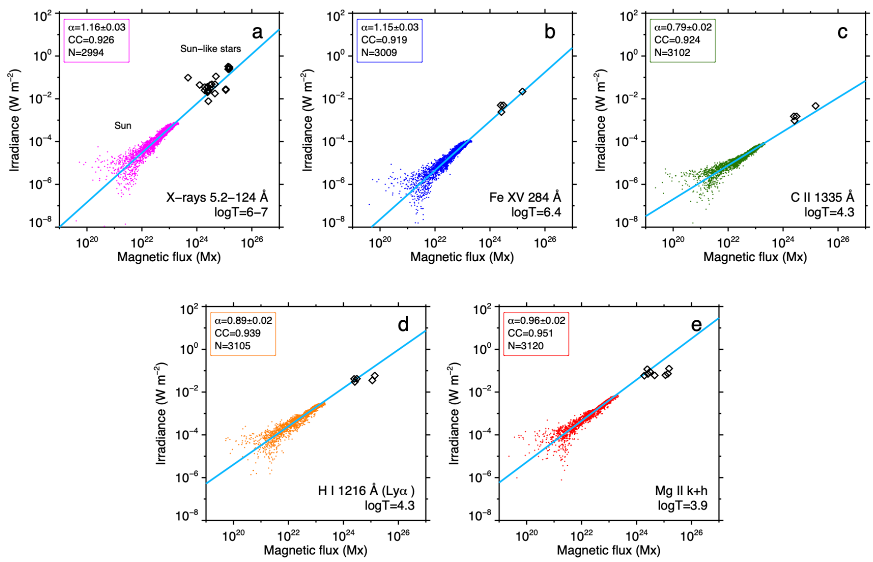

Figure 1: Mmagnetic flux and irradiances of five spectral lines for the Sun and Sun-like stars. In each panel, the straight line indicates the power-law fitting to the solar data (colored dots), which are compared to the stellar data (diamonds).