Persistence of flare-driven atmospheric chemistry on rocky habitable zone worlds

Howard Chen1,2, Zhuchang Zhan3, Allison Youngblood4, Eric T. Wolf4,5, Adina D. Feinstein6 and Daniel E. Horton1,2

Low-mass stars show evidence of vigorous magnetic activity in the form of large flares and coronal mass ejections. Such space weather events may have important ramifications for the habitability and observational fingerprints of exoplanetary atmospheres. Here, using a suite of three-dimensional coupled chemistry-climate model simulations, we explore effects of time-dependent stellar activity on rocky planet atmospheres orbiting G, K and M dwarf stars. We employ observed data from the MUSCLES campaign and the Transiting Exoplanet Survey Satellite and test a range of rotation period, magnetic field strength and flare frequency assumptions. We find that recurring flares drive the atmospheres of planets around K and M dwarfs into chemical equilibria that substantially deviate from their pre-flare regimes, whereas the atmospheres of G dwarf planets quickly return to their baseline states. Interestingly, simulated O₃-poor and O₃-rich atmospheres experiencing flares produce similar mesospheric nitric oxide abundances, suggesting that stellar flares can highlight otherwise undetectable chemical species. Applying a radiative transfer model to our chemistry-climate model results, we find that flare-driven transmission features of bio-indicating chemical species, such as nitrogen dioxide, nitrous oxide and nitric acid, show particular promise for detection by future instruments.

In recent years, large-scale observational campaigns such as the Kepler Space Telescope indicate that rocky planets are common1–5. A handful of these systems are known to reside within the circumstellar habitable zones of their host stars6,7 and are amenable to atmospheric spectroscopic measurements (for example, Kepler-186, Kepler-452, Proxima Centauri, TRAPPIST-1, LHS-1140 and TOI-700). Ongoing Transiting Exoplanet Satellite Survey (TESS) operations8 will discover many closer and brighter planetary systems, offering more terrestrial exoplanets for follow-up mass measurements and atmospheric characterization efforts9,10. However, the interpretation of remotely sensed atmospheric data will require making sense of a planet’s signals in context—that is, understanding of the interactions of atmospheric chemistry, physics, dynamics and thermodynamics within the space weather environment and electromagnetic radiation regime. For instance, strong stellar chromospheric activity from low-mass stars could influence attendant atmospheres via the dissociation, excitation and ionization processes associated with space weather events11,12, leading to substantial alteration of planetary atmospheres and chemical signatures13. Modifications of atmospheric chemistry can have a critical influence on the bulk atmospheric composition14,15, atmospheric dynamics16, surface radiation dosage17,18 and detectability of atmospheric species19.

Stellar activity—which includes stellar flares, coronal mass ejections (CMEs) and stellar proton events (SPEs)—has a profound influence on a planet’s habitability, primarily via its effect on atmospheric ozone. Stellar flares are rapid releases (lasting minutes to days) of coronal magnetic energy accompanied by bursts of electromagnetic radiation and accelerated ionized particle fluxes. Previous work has shown that although a single large flare (for example, AD Leonis Great Flare with UV-optical energy of 10¹⁴ erg; ref. 20) does not substantially affect an Earth-like planet’s habitability21, repeated secular flaring and CMEs, by way of ultraviolet emissions (at wavelength λ < 350 nm) and SPEs (at energy E > 100 MeV), could destroy a planet’s ozone layer within a few Earth years22. With the exception of the strongest flaring scenarios, time-independent models have predicted that initially Earth-like atmospheres should retain appreciable amounts of ozone that could efficiently filter out incident UVB and UVC radiation23. However, this conclusion stands in contrast to that of time-resolved models, in which nearly 90% of the stratospheric ozone column could be eroded, even with conservative assumptions in flare magnitude and frequency24.

In addition to the considerable influence of stellar flares on ozone, flares are likely to have observationally relevant effects on planetary atmospheres25. Remote detection of biological processes or, equivalently, the measure of thermodynamic chemical disequilibrium26,27, is linked to atmospheric chemistry, brightness temperature and stellar variability. In the search for signals of life, detection of either biosignatures (that is, atmospheric constituents that are the direct result of life processes28,29) or bio-indicators (that is, the photochemical derivatives of biosignatures) is sought. High-magnitude stellar flares may trigger disequilibrium chemistry and generate bio-indicating species through photo-excitation, photodissociation and/or strong mixing. For example, it has been hypothesized that enhanced accumulation of nitric acid (HNO₃) in a biologically active atmosphere experiencing flares could serve as a bio-indicator, as purely abiotic concentrations of HNO₃ in anoxic conditions should be low28,29. Abiotic nitric oxide (NO) and nitrogen dioxide (NO₂) production in O₂-depleted environments is also not expected to result in substantial atmospheric accumulation as their
production is mediated by collisions between molecular biogenic oxygen and nitrogen. In atmospheres dominated by \( \text{N}_2 - \text{O}_2 - \text{H}_2\text{O} \), however, stellar activity could highlight species such as \( \text{NO} \), \( \text{OH} \), \( \text{O}_3(\text{D}) \) and \( \text{CO}_2 \) to potentially detectable levels.\(^{19,22}\)

Previous efforts to understand the effects of stellar flares on planetary atmospheres underscore the value of single-column climate models. Their efficiency and speed allow for a wide sampling of the planetary parameter space. However, lower-dimensional models do not account for critical three-dimensional (3D) processes, including atmospheric circulation, large-scale mixing and cloud dynamics—factors that have substantial impact on the climate and chemistry of exoplanets, particularly for slow rotators orbiting late K dwarf and early M dwarf stars.\(^{30,32}\) Assessments of stellar chromospheric and coronal activity influences on planetary atmospheres are likewise inherently 3D problems; for example, the role of a magnetic field, inclusion of dynamical mixing, and illumination geometry. As such, 3D considerations are likely to have crucial consequences for flare influence predictions. Furthermore, the majority of previous exoplanet–flare–habitability studies have used UV observations from a single, high-magnitude \(10^{34}\) erg superflare (\( \text{AD Leonis} \); refs. 7,20) that is unlikely to be representative of typical stellar flaring behaviour. Incorporating UV flare spectra and light curve temporal evolution using more typical flaring behaviour may offer new insights into the photochemical characteristics of habitable zone planets.\(^{44,46}\)

To better understand interactions between flaring stars and their attendant planets, in this study we employ a 3D global Earth system chemistry–climate model (CCM), the Whole Atmosphere Community Climate Model (WACCM; ref. 1). We simulate nitrogen-dominated rocky exoplanetary atmospheres experiencing time-dependent UV activity and proton events around G, K and M dwarf stars (Extended Data Figs. 1–3). Owing to (1) stationary substellar cloud formation that prevents runaway greenhouse states near the inner edge of the habitable zone,\(^{33,35}\) (2) decreased ice–albedo feedbacks that inhibit total glaciation near the outer edge of the habitable zone,\(^{37,38}\) and (3) increased nutrient replenishment via oceanic upwelling,\(^{40}\) previous 3D studies have demonstrated that slowly and synchronously rotating ocean-covered planets have increased habitability potential. With the inclusion of time-dependent stellar flares, the results from this work further the notion that slowly and synchronously rotating planets are favourable targets for future instruments.

**Numerical set-up**

We perform simulations of rocky exoplanetary atmospheres orbiting G, K and M star archetypes (Sun-like star, HD85512 and TRAPPIST-1). For each planetary scenario, we test different oxygenation states, magnetosphere strengths and stellar activity levels (Supplementary Table 1 and Extended Data Figs. 2 and 3). Pre-flare baseline atmospheric compositions are: \( \text{N}_2 \) (78%), \( \text{CH}_4 \) (0.701 parts per million by volume (ppmv)), \( \text{N}_2 \text{O} \) (0.273 ppmv) and \( \text{CO}_2 \) (288 ppmv). We focus on three different scenarios: (1) a magnetized rapidly rotating planet around a Sun-like star (which we refer to as G-star planet), (2) an unmagnetized slow rotator around HD85512 (K-star planet) and (3) a weakly magnetized rapidly rotator around TRAPPIST-1 (M-star planet). The latter two scenarios assume synchronous rotation. For each scenario, we simulate the effects of \( \text{O}_2 \)-rich (modern-Earth-like) and \( \text{O}_2 \)-poor (Proterozoic-Earth-like) initial atmospheres. Configurations and boundary conditions were chosen for self-consistency; that is, simulated configurations follow from known physics. For example, greater orbital separations of synchronously rotating planets around early M dwarfs imply slower rotation (compared with those around late M dwarfs). Without rotation-induced convection of conducting inner core fluids (that is, a magnetic dynamo), these planets are unlikely to sustain strong planetary-scale magnetic fields.\(^{45}\) Thus, although we test the sensitivity of our results to a suite of input parameters and assumptions, the main text presents the most self-consistent simulation scenarios, corresponding to experiments 1, 4 and 8 in Supplementary Tables 1 and 2.

Steady-state stellar spectral energy distributions from the 1850 Solar Irradiance spectrum,\(^{46}\) TRAPPIST-1 (M8V, effective temperature \( T_{\text{e}} = 2,511 \) K; Wilson et al., manuscript in preparation) and HD 85512 (K6V; \( T_{\text{e}} = 4,715 \) K; ref. 43) are used as inputs to the CCM. To compute time-dependent activity (Fig. 1), we use a measurements of the ultraviolet spectral characteristics of low-mass exoplanetary systems (MUSCLES) flare generator\(^{45}\) and observed TESS flare data identified by a convolutional neural network. Red crosses mark high-probability flares (>90% confidence). Sample MUSCLES spectra used in model simulations for flares with two different approximate energies during their impulsive phases.

**Fig. 1 | Observed flare light curves and spectra used as inputs for CCM simulations.**

a. Flare-driven atmospheric ionization rates produced via power-law extrapolations for large flares (\( E > 10^{34} \) erg) from the MUSCLES survey. Data that underpin the main text are labelled ‘main’, whereas data approaching the activity level of Proxima Centauri are labelled ‘active’ (Methods). The dashed black line connects the ‘main’ input ionization rates and the solid black line connects those of the ‘active’. b. Observed TESS light curves from TIC 1636399 identified by a convolutional neural network. Red crosses mark high-probability flares (>90% confidence). c. Sample MUSCLES spectra used in model simulations for flares with two different approximate energies during their impulsive phases.
We first report the effects of MUSCLES-derived stellar flares on our self-consistent scenarios. We then explore the effects of observed TESS flares, discuss the coupled effects of atmospheric transport and present results for key flare-modulated chemical species. Next we compare and contrast flare-induced differences between O$_2$-rich versus O$_2$-poor atmospheres and moist greenhouse states versus temperate states. Finally, we discuss the observational implications of our results. See the Supplementary Information for the complete simulation set-ups and input data.

**3D effects of large stellar flares**

We find that strong stellar flares drive dramatic transient and steady-state changes in stratospheric and mesospheric chemistry, particularly in nitrogen and hydrogen oxide reservoirs. Our results show that energetic flares ($E > 10^{33}\,\text{erg}$ and proton fluences $> 10^{14}\,\text{cm}^{-2}$) have profound impacts on atmospheric species such as nitric oxide (NO), hydroxide (OH) and ozone (O$_3$) (Figs. 2 and 3 and Extended Data Fig. 4; experiments 1, 4 and 8 in Supplementary Table 1). On unmagnetized K- and M-star planets in particular, modelled stellar flares modulate the atmospheric concentrations of many photochemically important species and ultimately establish new chemical steady-state regimes that substantially deviate from their pre-flare compositions (Fig. 3m and Extended Data Fig. 4m). In contrast, flares do not substantially perturb the atmospheric compositions of magnetized G-star and TESS planets (Fig. 2m; Extended Data Fig. 5).

Simulated mesospheric nitrogen oxides such as NO, derived from reactions initiated by precipitating electrons\(^4\), are orders of magnitude more abundant on K- and M-star planets (Fig. 3a–d and Extended Data Fig. 4a–d; experiments 4 and 8 in Supplementary Table 1) than those around G stars (Fig. 2a–d; experiment 1 in Supplementary Table 1). This is the combined result of the greater...
latitudinal extents of proton deposition for weakly or unmagnetized planets (Methods), steady-state inputs of UVB spectra, illumination geometries and planetary circulation regimes.

The circumstellar UV photochemical environment and slow rotation of K- and M-star planets lead to the persistence of mesospheric NO. NO mixing ratios on our simulated K- and M-star planets do not return to their pre-flare levels after a large flare (Fig. 3m), whereas NO on G-star planets returns to pre-flare levels within 50 days (Fig. 2m). Enhanced simulated global-mean NO lifetimes on M-star planets are due to lesser emission of UVB radiation ($\lambda < 280$ nm) by their host stars, which promotes O(1 D) formation, reducing an OH sink (as $H_2O_v + O(1D) = 2OH$, where $v$ indicates vapour). In addition, prolonged NO lifetimes on slowly rotating K-star planets are probably due to thermally driven radial day-to-night advection that transports produced substellar NO to the nightside, where it is temporarily stored. Here, daytime nitrogen–hydrogen oxide chemistry, such as NO + HO, and NO + NO, photolysis, is averted (Methods), leading to the time-averaged enhancement of NO abundances. In contrast, rapid horizontal mixing and higher incident UVB radiation for planets around G stars ($P = 24$ h) leads to more efficient NO removal via reaction with ozone and direct titration (Fig. 2a–d).

The presence of $H_2O_v$, a canonical habitability indicator, could signify an active hydrological cycle. Photochemical and photolytic by-products of $H_2O_v$ such as stratospheric OH and thermospheric H are produced by flare-initiated ion chemistry chains\(^5\). In our simulations, we find that hydrogen oxide family constituents are particularly sensitive to magnetic field assumptions due to their short lifetimes. Different magnetic field deflection geometries and host star UV spectral energy distributions contribute to different

---

**Fig. 3 | Spatial and temporal atmospheric effects of repeated stellar flaring on a K-star planet.** a–l. Simulated global time-slice distributions of upper atmospheric NO (a–d), OH (e–h) and O$_3$ (i–l) mixing ratios. m, n. Global average time-series (m) that result from exposure to flares with time-evolving proton fluences (n). The simulated planet rotates around K star HD85512 synchronously and does not have a magnetic field. NO and OH mixing ratios are reported at 0.1 hPa, whereas O$_3$ mixing ratios are reported at 1.0 hPa. Spherical projections are centred on 40° N and 225° longitude. The red cross in a denotes the substellar point.
OH mixing ratio distributions (Figs. 2e–h and 3e–h). During large stellar flares, stratospheric and mesospheric polar OH mixing ratios in the magnetized G-star planet simulation are ~$10^{-8}$, but are two orders of magnitude greater on the dayside of the unmagnetized K-star planet (~$10^{-6}$).

The existence and persistence of stratospheric ozone in planetary atmospheres is fundamentally important for the protection and development of surface life. Simulated K- and M-star planet atmospheres (Fig. 3a–l and Extended Data Fig. 4a–l) experience greater instantaneous ozone destruction compared with magnetized G-star planets (Fig. 2a–l). In the latter scenario with an Earth-similar magnetosphere, protons are funnelled to the polar regions by magnetic field lines, whereas protons directly interact with the dayside atmospheres of the K- and M-star planets, enhancing ozone destruction. These differences are further compounded by the redirection of protons to the polar nightside of G-star planets, initiating more sluggish chemical reactions than those that occur in the substellar regions of the unmagnetized planets. Ozone distribution differences between unmagnetized/weakly magnetized K- and M-star planets are due to the more active TRAPPIST-1 spectrum used (compared with that of HD85512), rapid horizontal mixing of chemical species and strengthened downward transport on M-star planets.

To assess the role of flare frequency on ozone retention, we simulate three flare frequency assumptions (experiments 8, 10 and 11 in Supplementary Table 1 and Extended Data Fig. 3). For stellar activity approaching that of an optically inactive M dwarf (that is, with cumulative flare index $\alpha = 0.7$; MUSCLES sample), the computed total ozone column (Methods) of the M-star planet gradually transitions to a depleted regime and establishes a new chemical steady state (Extended Data Fig. 6). For stars with activity levels similar to Proxima Centauri and AD Leo ($\alpha = 0.54$), we find that the ozone column experiences abrupt destruction from ~300 Dobson nits (DU) to ~106 DU over ~200 Earth days due to rapid erosion by incident stellar protons (Extended Data Fig. 6). Our results could thus be used by observers to tie a measured flare frequency to cumulative effects on a planet’s atmosphere.

In addition to modelled flares, we use observed flares from the first TESS data release, specifically M dwarfs TIC 671393 and 1636399 over 20–30 days of observation time (Extended Data Fig. 2; experiments 13 and 14 in Supplementary Table 1). We find...
that stellar flares from the TESS data lead to more subtle changes in the chemical composition of the attendant planets compared with the MUSCLES-based results that use modelled flare light curves with extrapolations to higher energies. For instance, simulated mesospheric ozone is halved at the end of the TIC 671393-based simulation (Extended Data Fig. 5), whereas the full 300 day simulation using MUSCLES data results in decrease by one to two orders of magnitude (Fig. 3). The absence of repeated energetic flares and the short timeframe of the observed TESS data drive lower production rates of NO and UV photolysis of ozone. This conclusion is consistent with analysis of TESS across ~24,000 samples, as very few stars exhibit continuous flares that exceed the $10^{34}$ erg threshold for ozone depletion.49

Apart from stellar characteristics, flare influences are also controlled by the interplay between planetary properties—between atmospheric mixing and photochemistry, for example. Fast rotation (period $P < 6$ days), as in the case of our modelled G-star planet scenario, induces standing tropical Rossby waves that disrupt meridional overturning circulation, as opposed to extratropical Rossby waves in the case of the M-star planets and weak planetary waves in the case of the K-star planet. Without rapidly rotating Earth-like planet deep wave breaking mechanisms or momentum injections into the stratosphere, slow-rotator stratospheric winds are effectively damped and prevent divergent meridional flow and planet-wide chemical transport, leading to the confinement of flare-induced species in the equatorial regions (Extended Data Fig. 7; ref. 46). However, fast rotation facilitates downward transport of ozone-depleting agents such as NO$_x$ into the mid-lower stratosphere (Extended Data Fig. 8a). Conversely, slow rotation (that is, the K-star planet) allows NO$_x$ to remain in the mesosphere/thermosphere (Extended Data Fig. 8b). The simulated descent of flare-induced species is analogous to the advection of Earth’s NO$_x$-rich air masses into the stratosphere, driven by the stratospheric polar vortex and large-scale eddies. Thus, although the presence or absence of a planetary magnetic field plays a key role in governing ozone destruction (as polar ozone could be replenished by efficient meridional circulation), our results indicate that slow rotation (that is, $P > 25$ days for an Earth-sized planet) can help maintain a stable global ozone layer against proton-initiated removal.

The elevated nitrogen and hydrogen oxides discussed above influence the formation and lifetimes of other atmospheric species such as N$_2$O, CH$_4$, HNO$_3$, and H$_2$O$_x$, especially for the K- and M-star planet scenarios. Effects on the G-star planet are generally less persistent, as can be seen from the relative 300 day mean deviation from
Around an actively flaring K star (HD85512) (Fig. 6a). We find greater detectability prospects for flare-induced nitrogen oxides (for example, NO, N$_2$O, NO$_2$ and HNO$_3$) on planets orbiting K stars compared to those orbiting G stars. This is primarily owing to the increased NO$_x$ lifetimes on K-star planets, stemming from the lower stellar UVB output of cooler stars and prevalence of nocturnal chemistry over daytime chemistry on slowly and synchronously rotating planets. The red curves contain variable amounts of simulated nitrogen oxide species, whereas the blue and purple curves contain no nitrogen oxides. Each grey label indicates the species responsible for the spectral feature below it. B field stands for planetary magnetic field.

This suggests that recurring flares via proton events could drive enhanced water loss through diffusion-limited escape even for planets that do not reside at the inner edge of the habitable zone. These putative non-Earth archetype scenarios demonstrate that flare-driven accumulation of nitrogen and hydrogen oxides could be reliable indicators of atmospheres dominated by N$_2$–O–H$_2$.O.

**Observational prospects and implications**

Planetary transmission spectra, using our chemistry-climate model outputs, demonstrate that stellar flaring induces spectral features of habitability indicators and biosignatures (Fig. 6). Here we assess the detectability of nitrogen compounds for two endmember atmospheric scenarios from our suite of CCM simulations. Specifically, we compare the transit signals of NO, N$_2$O, NO$_2$ and HNO$_3$ on an O$_2$-poor magnetized planet orbiting a Sun-like star against those on an O$_2$-rich unmagnetized planet orbiting a K dwarf. We find peak absorption depths of 2, 4, 3 and 6 ppm for the respective species in the latter scenario (Fig. 6b). Despite transit depth shifts occurring above the cold trap and thus not being muted by clouds, differences between pre-flare and flare peak features are less than the predicted noise floor of the James Webb Space Telescope (10–30 ppm; ref. 55). Moreover, partial overlap of NO and NO$_2$ features with those of CO$_2$ and H$_2$O at 4.3 and 5.5 μm obscures their signals. As such, detecting flare-driven biosignature fingerprints on synchronously rotating nitrogen-dominated Earth-sized exoplanets should await the development of larger telescopes with greater observing power and better instrument noise floor control (that is, with the noise floor pushed to ~1–2 ppm).

Other simulated spectral features, such as OH and O$_2$(1D), are probably only observable during or soon after a large flare, or in a system with a rapid succession of flares during transit measurements. This is due to the species’ short chemical lifetimes, relaxation timescales and rapid zonal mixing on non-synchronously rotating G-star planets. Transmission features of biosignatures such as CH$_4$
and O, are predicted to be greatly reduced, as they react strongly with nitrogen and hydrogen oxides26. Note that these transient features arise primarily from species abundance changes in the mesosphere and lower thermosphere, and not from the stratosphere or troposphere (Fig. 4). This finding is a result of our proton energy spectrum assumption (Methods). The use of different proton energy spectrum assumptions could alter particle deposition depth, whole-column species abundances and detectability.

Sudden increases in X-ray and extreme UV irradiation (1.0 < λ < 100 nm)—which can energize, ionize and dehydrate the upper atmosphere27—are also associated with CMEs and stellar superflares28,29. Thus, planets around active M dwarfs may quickly lose their major high-mean-molecular-weight species, whereas initially volatile-rich atmospheres around less active K dwarfs may be able to survive on geologic timescales30. Here, we find that the convolved effects of magnetic field strength, radiation environment and atmospheric circulation lead to substantial time-averaged (over ~1 Earth year) chemical perturbations on flare-modulated K- and M-star planets. This result underscores the importance of constraining the temporal evolution of the host star spectra and luminosity to assess exoplanetary habitability. Although we report the 3D effects of stellar flares on oxidizing atmospheres, strong flares could have other unexpected impacts on atmospheres with reducing conditions. For instance, hydrogen oxide species derived from stellar flares could destroy key anoxic biosignatures such as methane, dimethyl sulfide and carbonyl sulfide31, thereby suppressing their spectroscopic features. However, new ionization rate profiles derived from a prognostic ion chemistry model will be needed to conduct analogous studies in atmospheric compositions dissimilar to Earth's. More speculatively, proton events during hyperflares may reveal the existence of planetary-scale magnetic fields by highlighting particular regions of the planet (for example, the poles; Fig. 2a–c). By identifying nitrogen- or hydrogen oxide-emitting flux fingerprints during magnetic storms and/or auroral precipitation events, one may be able to determine the geometric extent of exoplanetary magnetospheres.

**Methods**

The US National Center for Atmospheric Research (NCAR) model WACCM was employed to simulate planetary atmospheres. Synthetic and observed flare time series and UV spectra are used as inputs to the climate model. Atmospheric transmission and emission spectra are computed using a radiative transfer model with updated molecular line lists.

**CCM.** To simulate planetary atmospheres, we employ WACCM32, a high-resolution version of the Community Earth System Model v1.2, developed by NCAR. The model solves the primitive equations of fluid dynamics and thermodynamics, and includes self-consistent coupling of dynamics, chemistry, radiation and thermodynamics. We use the Community Atmosphere Model v4 (CAM4) with the following modules: Community Atmospheric Model Radiative Transfer (CAMRT) radiation scheme33, the Zhang-McFarlane scheme for deep convection34 and the Hack scheme for shallow convection35. The chemistry model is version 3 of the Modules for Ozone and Related Chemical Tracers (MOZART) chemical transport model36, which includes neutral and ionic constituents linked by 217 reactions. All surface gas fluxes are fixed at 1850 pre-industrial values, as industrial emission impacts ocean heat transport on tidally locked worlds is minimized by the north–south (for example, vegetation, land type and albedo). Excluding ocean dynamics modern-Earth continental configurations, including pre-industrial surface features but no advection. The Community Land Model (CLM) v4 is used to model the native broadband radiation model of CAM4 expanding on both longwave and shortwave radiative parameterizations from those of CAM3 and CAM437. WACCM uses thermodynamic equilibrium (LTE) and non-LTE heating and cooling rates in the extreme UV and infrared25. In the shortwave regime (0.05 nm to 100 μm; refs. 38,39), radiative heating and cooling are sourced from photon absorption, as well as photolytic and photochemical reactions. The native broadband radiation model of CAM4 is employed and not the newly introduced IR absorption coefficients38. Such treatment is appropriate at temperatures 150 °C < T < 340 K, which is the primary regime of interest in this study.

**Planetary magnetic field assumptions.** To test the influence of a gravitational field on the global incident charged particle distribution, we parameterize the presence of planetary-scale magnetic fields as follows.

**Magnetized scenario.** Protons are injected at polar latitudes (>60°) across all longitudes, as incident particles are guided by the magnetic field lines to higher latitudes. This means that both the day- and nightside receive comparable proton fluxes due to the deflection geometry. Weakened (or anomalously) magnetized scenario. Protons are injected in three different areas, with the assumption that the magnetic field's direction fluctuates wildly and originates from several poles: (1) between 30° and 60° latitude, 120° and 240° longitude; (2) between –30° and –60° latitude, 120° and 240° longitude; and (3) between 30° and –30° latitude, 300° and 60° longitude.
Unmagnetized scenario. Protons are directly injected on the substellar hemisphere between 90° and 270° longitude. No magnetic field effect occurs in this scenario.

In all the above cases, the vertical distribution of the ion pair production rate (that is, the proton spectrum) is based on Earth observations by Michelson Interferometer for Passive Atmospheric Sounding instrument and the Geostationary Operational Environmental Satellite (GOES)-11 during the 31 October 2003 geomagnetic storm156. The calculation of self-consistent particle energy spectra (for example, refs. 155,156) and far UV (FUV) emission relationships will be conducted in future work.

Stellar spectra. The effects of stellar activity across three spectral types are investigated: G, K and M. For G-star simulations, we use an observed and reconstructed solar irradiance spectrum19. The input spectrum version is fixed in the year 1850 and no observed irradiance cycle is included. For K- and M-stars, two spectral types that bracket the endmember range of low-mass stars were used: (1) TRAPPIST-1 (M8V; \( T_{\text{eff}} = 2,511 \text{ K} \)) data from the Mega-MUSCLES survey (Wilson et al., manuscript in preparation) and (2) HD 85512 (K6; \( T_{\text{eff}} = 4,715 \text{ K} \)) stellar SED from the MUSCLES survey (https://archive.stsci.edu/prepds/muscles/version/2.2; refs. 157,158). Both spectra are binned at 1 Å resolution with negative flux bins removed via iterative averaging as statistical noise in the low-signal regions and the subtracted background level can result in negative fluxes. The presence of statistical noise in the signal and subtracted background levels necessitates this approach105. Both stellar spectra are constant in time with exception of the UV and near UV (NVUV) wavelength range (110–320 Å), which vary with the occurrence of flares (see below). We investigate wavelength-independent or wavelength-dependent flares with a total energy below 1030 erg and peak ionization rates in the thermosphere and the ionosphere105,106. As such, we predict where flares occur using these models. Flare amplitudes and equivalent durations were calculated by fitting a Gaussian rise and exponential decay profile on a local region of the light curve around the flare. The use of convolutional neural networks is advantageous as it can identify both large (\( \delta > 10^4 \text{ s} \)) and small (\( \delta < 10^4 \text{ s} \)) flares. Whereas the former is the focus of this study, small flares have important cumulative effects over longer timescales. All code used is part of the open-source stella Python package version 143.

Previous multi-wavelength observations of stellar activity suggest that optical events can serve as proxies for the initial heating of the chromosphere, as optical flares are found to precede the X-ray, EUV and UV flares of the impulsive phase107,108. Thus, although the TESS data do not provide UV spectra, we assume that the UV flare frequencies over the course of 20 years are qualitatively similar to those in the observed IR and optical regimes. Simulations that use the TESS data as inputs assume TRAPPIST-1 steady stellar SED from the Mega-MUSCLES survey (Wilson et al., manuscript in preparation).

Proton fluences and ionization rates. Incident charged particles of stellar origin are associated with large flares and CME-like events34,109,110. Although direct observations of energetic particle emissions during CMEs are not available (that is, only signatures of CMEs are observable; ref. 111), we follow previous studies by using the scaling laws based on near-Earth satellite data. We assume that all of the particles are protons. We compute the expected peak proton fluences from the Sun's SED of stellar flares\(^5\):

\[
\log F_{p, 10 \text{MeV}} = 1.20 \log F_{\text{SIUV}} + 3.27
\]

where \( F_{p, 10 \text{MeV}} \) is the proton flux. The derived fluences all follow the M dwarf flare-model-generated light curve shapes/durations. As there is a linear relationship between the proton flux and production rate of ion pairs\(^5\), we scaled the input ionization rates comparing our estimated proton fluence with that of the 2003 Halloween SPE (an order of magnitude lower than the Carrington event in 1719; refs. 112,113). The ion pair production rates, provided in the Solar Influence for SPARC (newly updated in March 2019) and derived from proton flux measurements by GOES 11 instrument, are then applied as daily averages during each flare peak. Daily cadences are appropriate in this pilot study as the cascading NOx and HOx reactions are much faster than the flare and model steps, but future work should employ higher temporal resolutions to better resolve stellar activity on hourly timescales (for example, ref. 114).

Other methods to calculate ionization rates due to solar or galactic-sourced cosmic rays (such as the air-shower approach)\(^1\) have shown to perform well with the approach taken here and those in previous studies. Note that the majority of stellar and exoplanetary studies use the same peak size distribution functions from solar events\(^115,116\). However, large discrepancies exist between published peak size distributions due to the different underlying physical mechanisms driving these events\(^117\). Thus the conclusions established from photochemical models, even with the same flare inputs, would probably be contingent on the specific function used.

Stellar UV and proton event-initiated atmospheric chemistry. WACCM includes a range of chemical reactions necessary to fully account for the effects of

\[
\nu = \frac{\delta_t}{\delta_t + \alpha} \nu_{\text{ref}}
\]
stellar activity. The interaction of UV photons with trace gases typically leads to
dissociation via photolysis:\(^4\):
\[
\text{H}_2\text{O} + \nu(175 < \lambda < 200 \text{ nm}) \rightarrow \text{H} + \text{OH}
\]
\[
\text{O}_3 + \nu(\lambda < 320 \text{ nm}) \rightarrow \text{O}_2 + \text{O}(^1\text{D})
\]
Some important daytime(side) photochemical reactions are\(^4\):
\[
\text{O}(^1\text{D}) + \text{H}_2\text{O} \rightarrow 2\text{OH}
\]
\[
\text{HO}_2 + \text{NO} \rightarrow \text{H} + \text{NO}_2
\]
\[
\text{NO}_2 + \nu(\lambda < 420 \text{ nm}) \rightarrow \text{NO} + \text{O}(^1\text{P})
\]
Particle precipitation due to SPEs also influences atmospheric chemistry: SPEs produce charged particles (protons and secondary electrons) that cause excitation and the subsequent dissociation of ambient gaseous constitutents. Ground-state and excited-state nitrogen are produced via\(^4\):\(^6\):
\[
\text{N}_2 + e^- \rightarrow 2\text{N} (^4\text{S}) + e^-
\]
or
\[
\text{N}_2 + e^- \rightarrow 2\text{N} (^2\text{D}) + e^-
\]
where \(e^-\) represents secondary electrons produced by incident protons. We assume that 1.25 N atoms are produced per ion pair (specifically 0.55 N(4S) ground-state atoms and 0.7 N(2D) excited-state atoms; ref.\(^4\)).

Excited and ground-state nitrogen can subsequently produce NO via:\(^4\):
\[
\text{N}_2 (^2\text{D}) + \text{O}_2 \rightarrow \text{NO} + \text{O}(^3\text{P})
\]
\[
\text{N}_2 (^4\text{S}) + \text{O}_2 \rightarrow \text{NO} + \text{O}(^3\text{P})
\]
or remove NO via:
\[
\text{N}_2 (^4\text{S}) + \text{NO} \rightarrow \text{N}_2 + \text{O}(^3\text{P})
\]
Two \(\text{HO}_2\) species are produced per ion pair. Parameterization of prognostic ionic water cluster reaction networks is done via\(^6\):
\[
\text{H}_2\text{O} + \text{ion}^+ \rightarrow \text{H} + \text{OH} + \text{ion}^+
\]
Increase \(\text{HO}_4\) species lead to catalytic ozone destruction in the stratosphere via:
\[
\text{OH} + \text{O}_3 \rightarrow \text{HO}_2 + \text{O}_2
\]
\[
\text{HO}_2 + \text{O} \rightarrow \text{OH} + \text{O}_2
\]
and the mesosphere via:
\[
\text{H} + \text{O}_3 \rightarrow \text{OH} + \text{O}_2
\]
\[
\text{OH} + \text{O} \rightarrow \text{H} + \text{O}_2
\]
While OH and H are act on short timescales (hours), the prolonged lifetimes of \(\text{NO}_3\) species can deplete stratospheric ozone via:
\[
\text{NO}_3 + \text{O}_3 \rightarrow \text{NO}_2 + \text{O}_2
\]
\[
\text{NO}_2 + \text{O} \rightarrow \text{NO} + \text{O}_2
\]
Apart from contributing to ozone loss, enhanced NO and OH during large stellar flares can also modulate the abundance of other important biosignatures and habitability indicators (see, for example, refs.\(^4\)).\(^6\) Example reactions are:
\[
\text{N} + \text{NO}_2 \rightarrow \text{N}_2\text{O} + \text{O}
\]
\[
\text{NO}_2 + \text{OH} + \text{M} \rightarrow \text{HNO}_3 + \text{M}
\]
\[
\text{CH}_4 + \text{OH} \rightarrow \text{CH}_3 + \text{H}_2\text{O}
\]
where \(\text{NO}_3\) can be photochemically derived from the cascading \(\text{N}_2\) dissociation initiated by SPEs, whereas OH can come from water vapour photolysis, ion chemistry, and the reaction between \(\text{H}_2\text{O} + \text{O}(^1\text{D})\). \(\text{NO}_2\) can also be produced from the reaction between NO and NH.

Atmospheric spectroscopy model. To translate WACCM output into observable predictions, we use the Simulated Exoplanet Atmosphere Spectra (SEAS) model (Z.Z. et al., manuscript in preparation) to compute atmospheric spectra. SEAS is a radiative transfer code that calculates the attenuation of photons by molecular absorption and Rayleigh/Mie scattering as the photons travel through a hypothetical exoplanetary atmosphere. The simulation approach is similar to previous work\(^5\).\(^6\). The molecular absorption cross-sections for \(\text{O}_2\), \(\text{H}_2\text{O}\), \(\text{CO}_2\), \(\text{CH}_4\), \(\text{O}_3\) and \(\text{H}_2\) are calculated using the HITRAN2016 molecular line list database\(^4\). The SEAS transmission spectra are validated through comparison of its simulated Earth transmission spectrum with that of real Earth counterparts measured by the Atmospheric Chemistry Experiment (ACE) data set\(^4\). For more details on SEAS, please see section 3.4 in Z.Z. et al. (manuscript in preparation).

Day-night mixing ratio and ozone column. Mixing ratio contrasts of various gases between the day- and night-side are defined as:\(^5\):
\[
\frac{C_{\text{night}} - C_{\text{day}}}{C_{\text{globe}}}
\]
where \(C_{\text{day}}\) is the diayside hemispheric mixing ratio mean, \(C_{\text{night}}\) the nightside mean and \(C_{\text{globe}}\) the global mean. We compute \(C_{\text{diff}}\) by vertically averaging the mixing ratios between 1 and 1 x 10\(^{-4}\) hPa.

The column number density of species \(i\) is defined as:
\[
N_i = \int n_i \text{d}z
\]
where \(n_i\) is the volume number density of species \(i\) and \(z\) is the vertical coordinate. Here, we compute the total ozone column by summing up the volume number density in all 66 levels. The number density of ozone in each level is calculated via:
\[
N_{O_3} = C_{O_3} \frac{N_A P_i}{RT_i}
\]
where \(C_{O_3}\) is the mixing ratio of ozone, \(N_i\) is Avogadro's number, \(R\) is the gas constant (8.31 J mol\(^{-1}\) K\(^{-1}\)) and \(P_i\) and \(T_i\) are the atmospheric pressure and temperature at level \(i\). The total ozone column is typically expressed in DU (1 DU = 2.686 x 10\(^{-5}\) m\(^{-2}\) or 2.686 x 10\(^{-4}\) cm\(^{-2}\)).

Data availability

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon request. The raw data are publicly available at https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html (MAST) and https://archive.stsci.edu/prepsds/muscles/ (MUSCLES) and the solar ion pair production rates are available at https://solarisheppa.geomar.de/solarprotonfluxes.

Code availability

The unmodified climate model used in this study is available for public download at http://www. cesm.ucar.edu/models/cesm1.2/cesm/doc/usersguide/x290.html. Components of the modified version of the climate can be obtained via ExoCam at https://github.com/storyofthewolf/ExoCAM and by request from E.T.W. (eric.wolf@colorado.edu). The stella package can be downloaded at https://github.com/af einstein20/stella. The remaining codes that support the results within this paper and other findings of this study are available from the corresponding author on request.

Received: 29 April 2020; Accepted: 29 October 2020; Published online: 21 December 2020

References

1. Borucki, W. J. et al. Kepler planet-detection mission: introduction and first results. Science 327, 977–980 (2010).
2. Kopparapu, R. K. A revised estimate of the occurrence rate of terrestrial planets in the habitable zones around Kepler M-dwarfs. Astrophys. J. Lett. 767, L8 (2013).
3. Mulders, G. D., Pascucci, I., Apai, D. & Ciesla, F. J. The exoplanet population observation simulator. I. The inner edges of planetary systems. Astron. J. 156, 24 (2018).
4. Hsu, D. C., Ford, E. B., Ragozzine, D. & Ashby, K. Occurrence rates of terrestrial planets orbiting FGK stars: combining Kepler DR25, Gaia DR2, and astrometry. Astrophys. J. Lett. 767, 977–980 (2010).
5. Bryson, S. et al. The occurrence of rocky habitable zone planets around solar-like stars from Kepler data. Preprint at https://arxiv.org/abs/2010.14812 (2020).
6. Kasting, J. F., Whitmire, D. P. & Reynolds, R. T. Habitable zones around main sequence stars. Icarus 101, 108–128 (1993).
Articles

18. Yamashiki, Y. A. et al. Impact of stellar superflares on planetary habitability. *Astro. J.* **157**, 113 (2019).

20. Hawley, S. L. & Pettersen, B. R. The great flare of 1985 April 12 on AD 20. Segura, A., Walkowicz, L. M., Meadows, V. S., Kasting, J. & Hawley, S. A. In *Handbook of Exoplanets* (eds Deeg, H. & Belmonte, J.) pp. 2995–3017 (Springer, 2018).

23. Linsky, J. L. Stellar model chromospheres and spectroscopic diagnostics. *Annu. Rev. Astron. Astrophys.* **55**, 159–211 (2017).

26. Airapetian, V. S. et al. Impact of space weather on climate and habitability of terrestrial type exoplanets. *Int. J. Astrobiol.* **19**, 136–194 (2020).

27. France, K. et al. The MUSCLES Treasury Survey. I. Motivation and overview. *Astrophys. J.* **820**, 89 (2016).

26. Linsky, J. L. Stellar model chromospheres and spectroscopic diagnostics. *Annu. Rev. Astron. Astrophys.* **55**, 159–211 (2017).

26. Airapetian, V. S. et al. Impact of space weather on climate and habitability of terrestrial type exoplanets. *Int. J. Astrobiol.* **19**, 136–194 (2020).

27. France, K. et al. The MUSCLES Treasury Survey. I. Motivation and overview. *Astrophys. J.* **820**, 89 (2016).

28. Tabataba-Vakili, F. S., Grenfell, J. L., Grießmeier, J. M. & Rauer, H. Atmospheric effects of stellar cosmic rays on Earth-like exoplanets orbiting an M dwarf. *Astron. J.* **157**, 2019.

29. Kasting, J. F. Runaway and moist greenhouse atmospheres and the evolution of Earth and Venus. *Icarus* **74**, 472–494 (1988).

30. Fauchez, T. J. et al. Impact of clouds and hazes on the simulated JWST transmission spectra of habitable zone planets in the TRAPPIST-1 system. *Astrophys. J.* **887**, 194 (2019).

31. Komacek, T. D., Fauchez, T. J., Wolf, E. T. & Abbot, D. S. Clouds will likely prevent the detection of water vapor in JWST transmission spectra of terrestrial exoplanets. *Astrophys. J.* **888**, L20 (2020).

32. Schwieterman, E. W. et al. Exoplanet biosignatures: a review of remotely detectable signs of life. *Astrophys. J.* **18**, 663–708 (2018).

33. Des Marais, D. J. et al. Remote sensing of planetary properties and biosignatures on extrasolar terrestrial planets. *Astrophys. J.* **2**, 153–182 (2001).

34. Tabataba-Vakili, F., Grenfell, J. L., Grießmeier, J. M. & Rauer, H. Atmospheric effects of stellar cosmic rays on Earth-like exoplanets orbiting M-dwarfs. *Astron. J.* **858**, A96 (2016).

35. Schreuer, M. et al. New insights into cosmic-ray-induced biosignature chemistry in Earth-like atmospheres. *Astrophys. J.* **862**, 6 (2018).

36. Yang, J., Cowan, N. B. & Abbot, D. S. Stabilizing cloud feedback dramatically expands the habitable zone of tidally locked planets. *Astrophys. J. Lett.* **877**, L45 (2013).

37. Shields, A. L., Bitz, C. M., Meadows, V. S., Joshi, M. M. & Robinson, T. D. Spectrum-driven planetary deglaciation due to increases in stellar luminosity. *Astrophys. J. Lett.* **785**, L9 (2014).

38. Checlair, J., Menou, K. & Abbot, D. S. No snowball on habitable tidally locked planets. *Astrophys. J.* **845**, 132 (2017).

39. Checlair, J. H., Olson, S. L., Jansen, M. F. & Abbot, D. S. No snowball on habitable tidally locked planets with a dynamic ocean. *Astrophys. J. Lett.* **884**, L46 (2019).

40. Olson, S. L., Jansen, M. & Abbot, D. S. Oceanographic considerations for tidally locked exoplanet life detection. *Astrophys. J.* **895**, 19 (2020).

41. Christensen, U. R., Holzwarth, V. & Reiners, A. Energy flux determines magnetic field strength of planets and stars. *Nature* **457**, 167–169 (2009).

42. Len, J., Beer, J. & Bradley, R. Reconstruction of solar irradiance since 1610: implications for climate change. *Geophys. Res. Lett.* **32**, 1–4 (2005).

43. France, K. et al. The MUSCLES Treasury Survey. I. Motivation and overview. *Astrophys. J.* **820**, 89 (2016).

44. Feinstein, A. D. et al. Flare statistics for young stars from a convolutional neural network analysis of TESS data. *Astrophys. J.* **160**, 219 (2020).

45. Youngblood, A. et al. The MUSCLES Treasury Survey. IV. Scaling relations for ultraviolet, Ca II K, and energetic particle fluxes from M dwarfs. *Astrophys. J.* **843**, 31 (2017).

46. Jackman, C. H. et al. Neutral atmospheric influences of the solar proton events in October–November 2003. *Geophys. Res. Space Phys.* **110**, A09S27 (2005).

47. Solomon, S., Rusch, D. W., Gerard, J. C., Reid, G. C. & Crutzen, P. J. The effect of particle precipitation events on the neutral and ion chemistry of the middle atmosphere: II. Odd hydrogen. *Planet. Space Sci.* **29**, 885–893 (1981).

48. Segura, A. in *Handbook of Exoplanets* (eds Deeg, H. & Belmonte, J.) pp. 2995–3017 (Springer, 2018).

49. Günther, M. N. et al. Stellar flares from the first TESS data release: exploring a new sample of M dwarfs. *Astrophys. J.* **159**, 60 (2020).

50. Carone, L., Keppens, R., Decin, L. & Henning, T. Stratosphere circulation on tidally locked ExoEarths. *Mon. Not. R. Astron. Soc.* **473**, 4672–4685 (2018).

51. Funk, B. et al. Downward transport of upper atmospheric NO into the polar stratosphere and lower mesosphere during the Antarctic 2003 and Arctic 2002/2003 winters. *Geophys. Res. Atm.**s** **110**, D24308 (2005).

52. Kasting, J. F. Runaway and moist greenhouse atmospheres and the evolution of Earth and Venus. *Icarus* **74**, 472–494 (1988).

53. Fauchez, T. J. et al. Impact of clouds and hazes on the simulated JWST transmission spectra of habitable zone planets in the TRAPPIST-1 system. *Astrophys. J.* **887**, 194 (2019).

54. Komacek, T. D., Fauchez, T. J., Wolf, E. T. & Abbot, D. S. Clouds will likely prevent the detection of water vapor in JWST transmission spectra of terrestrial exoplanets. *Astrophys. J.* **888**, L20 (2020).

55. Schwieterman, E. W. et al. Detection of transmission spectra of ocean Earths around M stars. *Astrophys. J.* **891**, 58 (2020).

56. Dong, C. et al. The dehydration of water worlds via atmospheric losses. *Astrophys. J.* **847**, L4 (2017).

57. Mordasini, C. Planetary evolution with atmospheric photoevaporation. I. Analytical derivation and numerical study of the evaporation valley and transition from super-Earths to sub-Neptunes. *Astron. Astrophys.* **638**, A52 (2020).

58. Davenport, J. R. A. The Kepler catalog of stellar flares. *Astrophys. J.* **829**, 23 (2016).

59. Yang, H. et al. The flaring activity of M dwarfs in the Kepler field. *Astrophys. J.* **849**, 36 (2016).

60. Kite, E. S. & Barnett, M. N. Exoplanet secondary atmosphere loss and revival. *Proc. Natl Acad. Sci. USA* **117**, 18264–18271 (2020).

61. Domagal-Goldman, S. D., Meadows, V. S., Claire, M. W. & Kasting, J. F. Using biogenic sulfur gases as remotely detectable biosignatures on anoxic planets. *Astrophys. J.* **110**, 419–441 (2011).

62. Neumeier, A. E. et al. The MUSCLES Treasury Survey. V. FUV flares on active and inactive M dwarfs. *Astrophys. J.* **867**, 71 (2018).

63. Peacock, S., Barnam, T., Shkolnik, E. L., Hauschildt, P. H. & Baron, E. Predicting the extreme ultraviolet radiation environment of exoplanets around low-mass stars: the TRAPPIST-1 system. *Astrophys. J.* **871**, 235 (2019).

64. Marsh, D. B. et al. Climate change from 1850 to 2005 simulated in CESM1(WACCM). *J. Clim.* **26**, 7372–7391 (2013).

65. Way, M. J. et al. Was Venus the first habitable world of our solar system? *Geophys. Res. Lett.* **43**, 8376–8383 (2016).
provided by the NASA Office of Space Science via grant number NNX13AC07G and by other grants and contracts.

Author contributions
H.C., E.T.W. and D.E.H. conceived and designed the study. H.C. conducted the numerical model simulations and data analysis. Z.Z. performed the radiative transfer model simulations. A.Y. provided stellar input data from the MUSCLES and Mega-MUSCLES surveys. A.D.F. performed the machine learning TESS data reductions. H.C. wrote the manuscript with input from all co-authors.

Competing interests
The authors declare no competing interests.

Additional information
Extended data is available for this paper at https://doi.org/10.1038/s41550-020-01264-1.
Supplementary information is available for this paper at https://doi.org/10.1038/s41550-020-01264-1.
Correspondence and requests for materials should be addressed to H.C.
Peer review information Nature Astronomy thanks Antigona Segura and Eric Hébrard for their contribution to the peer review of this work.
Reprints and permissions information is available at www.nature.com/reprints.
Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.
© The Author(s), under exclusive licence to Springer Nature Limited 2020
Extended Data Fig. 1 | Input broadband (a) and UV (b) spectral energy distributions for the Sun, HD85512, and TRAPPIST-1. The Sun represents the G-star archetype, HD85512 a K-star, and TRAPPIST-1 a late M-star. We refer to the stellar spectral types these stars represent (G-star, K-star, and M-star) instead of the specific star in the main text and throughout the paper.
**Extended Data Fig. 2 | Timeseries of TESS lightcurves used in this study.** The stellar data used are those of TIC 671393 (a) and TIC 1636399 (b), showing identified flares by orange ‘×’s. Flares are identified by a convolutional neural network algorithm described in Feinstein et al. (2020).
Extended Data Fig. 3 | Three scenarios of input vertical-mean ionization rates to explore the effects of flare frequency. Three different assumptions are investigated: $\alpha = 0.7, 0.82, 0.54$. Supplementary Table 1 lists the specific experiments and their assumed flare frequency.
Extended Data Fig. 4 | Spatial and temporal atmospheric effects of repeated stellar flaring on an M-star planet. Simulated global time slice distributions of upper atmospheric NO (a–d), OH (e–h), and O₃ (i–l) concentrations and their global average time-series (m) that result from exposure to flares with time-evolving proton fluences (n). The simulated planet rotates around M-star TRAPPIST-1 synchronously and has a weak magnetic field, and OH mixing ratios are reported at 0.1 hPa, whereas O₃ mixing ratios are reported at 1.0 hPa. Spherical projections are centered on 40°N latitude and 225° longitude. Red cross denotes the substellar point.
Extended Data Fig. 5 | Temporal evolution of global-mean mixing ratios of NO, OH, and O₃ experiencing TESS flares. Result demonstrate that small flares over a short timespan do not substantially affect exoplanetary atmospheres. NO and OH mixing ratios are reported at 0.1 hPa, whereas O₃ mixing ratios are reported at 1.0 hPa.
Extended Data Fig. 6 | Global-mean vertical profiles of ozone number density at three different stellar flare frequencies. These results show the cumulative effect (300 Earth days) of repeated stellar flares. Results that assume $\alpha$ approaching those of observed MUSCLES stars ($\alpha = 0.7$) established a new chemical equilibrium, whereas those using a values close to very active stars ($\alpha = 0.54$) have their ozone layers rapidly depleted.
Extended Data Fig. 7 | Zonal mean of zonal wind, O₃ mixing ratios (10⁻⁸), and meridional circulation stream functions for hypothetical O₂-rich planets around a G-star, K-star, and M-star as denoted. Results demonstrate the convolved effects of dynamics and atmospheric chemistry.
Extended Data Fig. 8 | NO concentration averaged over the poles (|latitude|>65°) as a function of time and pressure for hypothetical O₂-rich planets. The rotation periods of these simulations are 24 hours, 92 Earth days, and 4.32 Earth days around a G-dwarf (a), K-dwarf (b), and M-dwarf (c) star. Note the log₁₀-scale.