Space Weather Affected Habitable Zones (SWAHZ)

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Introduction: Recent detection of terrestrial-type exoplanets with approximately Earth sizes and masses within the climatological habitable zones (CHZ) provides the first glimpse into the potential habitability of these worlds. The classical definition of the CHZ invokes the total amount of thermal energy emitted by stellar photospheres received by the planet at a given point in time, but largely ignores the impact of the star's non-thermal emission and the level of its magnetic energy on the thickness of an exoplanet's atmosphere and its habitability. Atmospheres of exoplanets in the habitable zones around active young G-K-M stars are subject to extreme *X-ray* and EUV (*XUV*) fluxes from their host stars that can initiate atmospheric erosion. Atmospheric loss affects exoplanetary habitability in terms of surface water inventory, atmospheric pressure, the efficiency of greenhouse warming and the dosage of the UV surface irradiation. Thermal escape models suggest that exoplanetary atmospheres around active K-M stars should undergo massive hydrogen escape [1], while heavier species including oxygen will accumulate forming an oxidizing atmosphere. Here we show that non-thermal oxygen ion escape could be as important as thermal, hydrodynamic H escape in removing the constituents of water from exoplanetary atmospheres under supersolar *XUV* irradiation.

Effects of XUV-EUV Driven Mass Loss of O$^+$.

In the region above an Earth-size planet's exobase, the layer where collisions are negligible, the incident *XUV* flux ionizes atmospheric atoms and molecules and produces photoelectrons. The upward propagating photoelectrons outrun ions in the absence of a radially directed polarization electric field and forms the charge separation between electrons and atmospheric ions. Thus, a radially directed polarization electric field is established that enforces the quasi-neutrality and zero radial current. For ionospheric ions with energies over 10 eV, the polarization electric field cancels a substantial part of the Earth's gravitational potential barrier, greatly enhancing the flux of escaping ions and forming an ionospheric outflow.

We apply this approach to couple the ion hydrodynamics of the Polar Wind Outflow Model (*PWOM*) to the latest version of the SuperThermal Electron Transport (*STET*) code [2 and references herein]. To treat the *XUV* driven photoelectron production and transport properly, we apply STET to calculate the superthermal particle population formed via photoionization and its collisional coupling with the thermal population and the neutral atmosphere. Our coupled *PWOM* and *STET* model uses *MSIS-90* (mass spectrometer and incoherent scatter) empirical model developed for the Earth atmosphere [3] as an input for *PWOM & STET* to obtain the neutral densities including O, O_2 and N_2 and temperatures. To properly treat photodissociation and photoionization of major species we used the *XUV* emission input in the range between 5-1750 Å. Specifically, O$^+$ ions form due to photoionization of atomic oxygen via photons with wavelengths ~ 300-600 Å and collisions with photoelectrons.

We have developed 4 models with the stellar *XUV* input flux expressed in terms of the total *XUV* flux, F_0, of the Sun at the average level of magnetic cycle. The flux superthermal photoelectrons with the energies extending to 70 eV increases approximately linearly with the input *XUV* flux. *PWOM* then uses *STET*'s representation of the superthermal electrons to model the ionized atmosphere escape rates.

In order to evaluate the effect of the base temperature on the O$^+$ outflow rate, we calculated two escape models for the XUV flux of $10F_0$ for these two exobase temperatures. We find that as we increase the base temperature by a factor of 2, the resulting O$^+$ outflow rates increase by a factor of 10. We then calculated the 4 models for an exoplanet with the same atmospheric properties and mass as the current Earth (Earth twin) irradiated by *XUV* fluxes at 2, 5, 10 and 20 F_0 respectively at T_{base} = 2000K. Because the base temperature of the neutral atmosphere is > 2000K at fluxes higher than 10 F_0, the model output represents a lower limit on the outflow rates along the magnetic field line. The total loss rate of O$^+$ at *h*=1000 km is found from the integration of this value over the whole area, *S*, region of the polar region as $\dot{M} = \rho VS$, where ρ is the density of the oxygen ions at that altitude, *V* is the O$^+$ ion bulk velocity. We find that the loss rate of O$^+$ and N$^+$ is scaled with the input flux as

$$\dot{M} \text{ (in g/s)} \sim 1.6 \times 10^4 F_{XUV} \text{ (in erg/cm}^2\text{/s)}.$$

This loss rate is comparable to the thermal loss of hydrogen at *XUV* fluxes ~ $20F_0$ at the inner edge of CHZ if radiative cooling and the transition from hydrodynamic to Jeans escape are accounted for an ~ 1 Earth mass planet (Owen and Mohanty 2016).

Conclusions.

Our results imply that the *CHZ* definition can only be applied to mid-age *K-G* main-sequence stars for which the *XUV* fluxes at the distances of their *CHZs* are small enough (< $5F_0$) to be significant for the atmospheric loss at evolutionary time scales. For higher fluxes, atmospheric loss rates are high enough to affect atmospheric evolution, and to reflect this impact,it may be useful to extend *CHZ*s to Space Weather Affected Habitable Zones (*SWAHZ*s) [6]

References

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