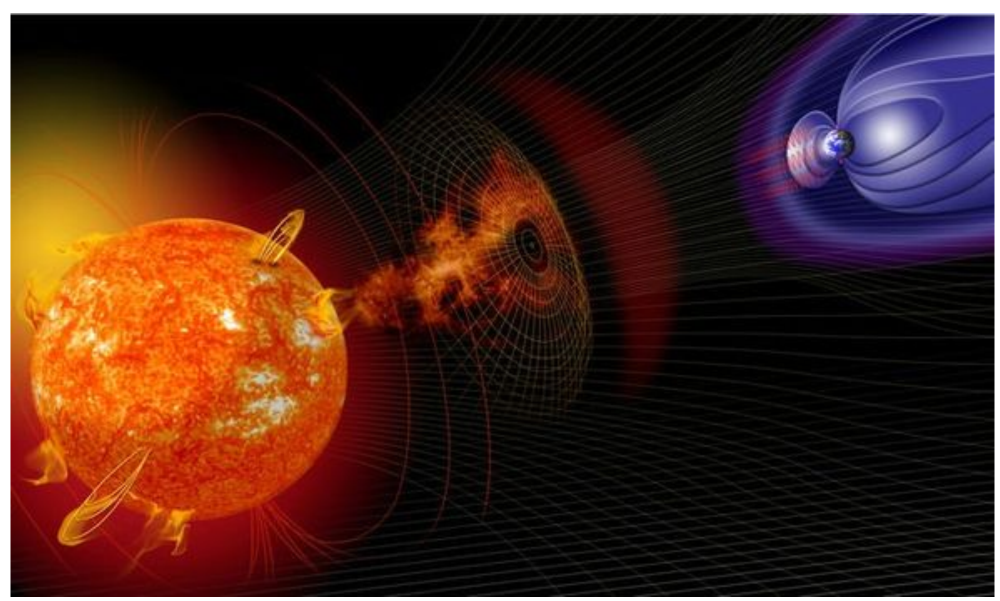
Stellar Proton Events and Exoplanetary Habitability

Dimitra Atri
Center for Space Science
New York University, Abu Dhabi

atri@nyu.edu



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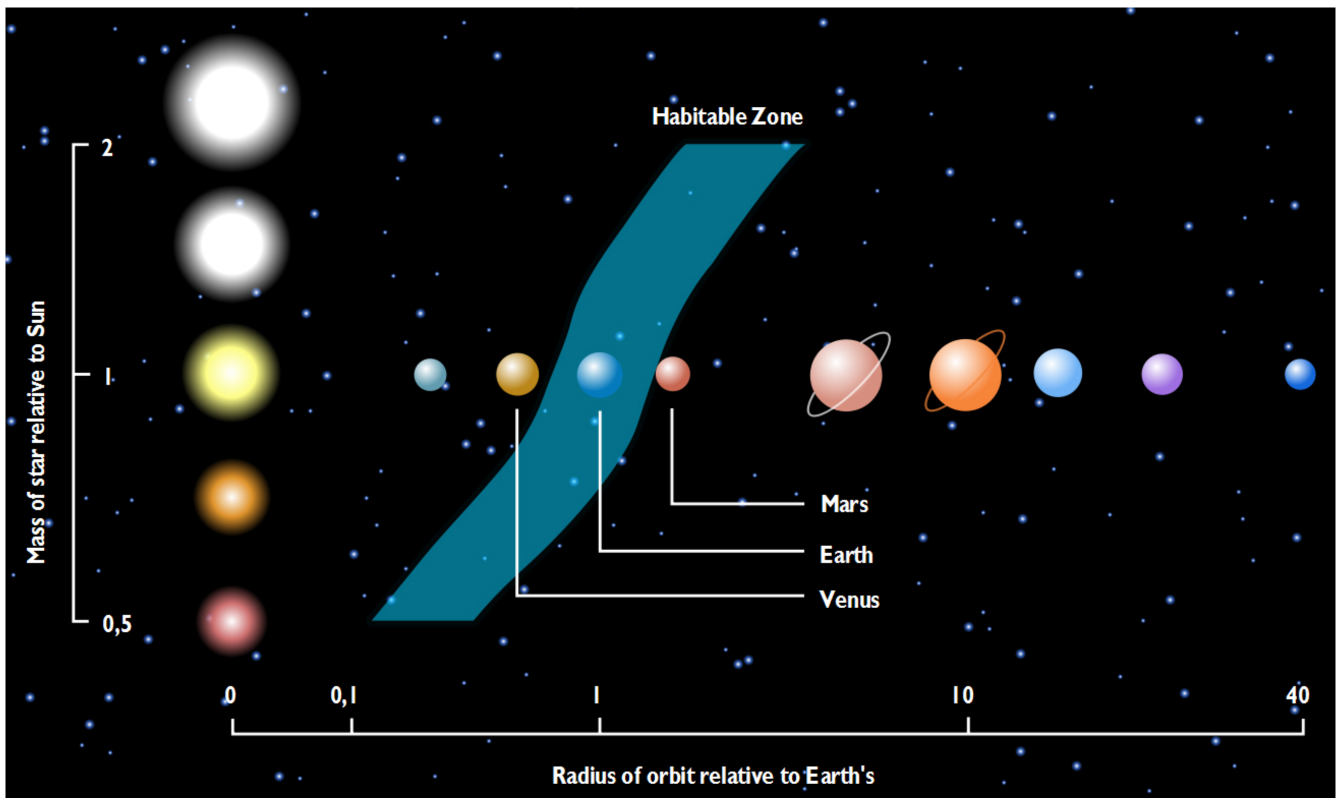
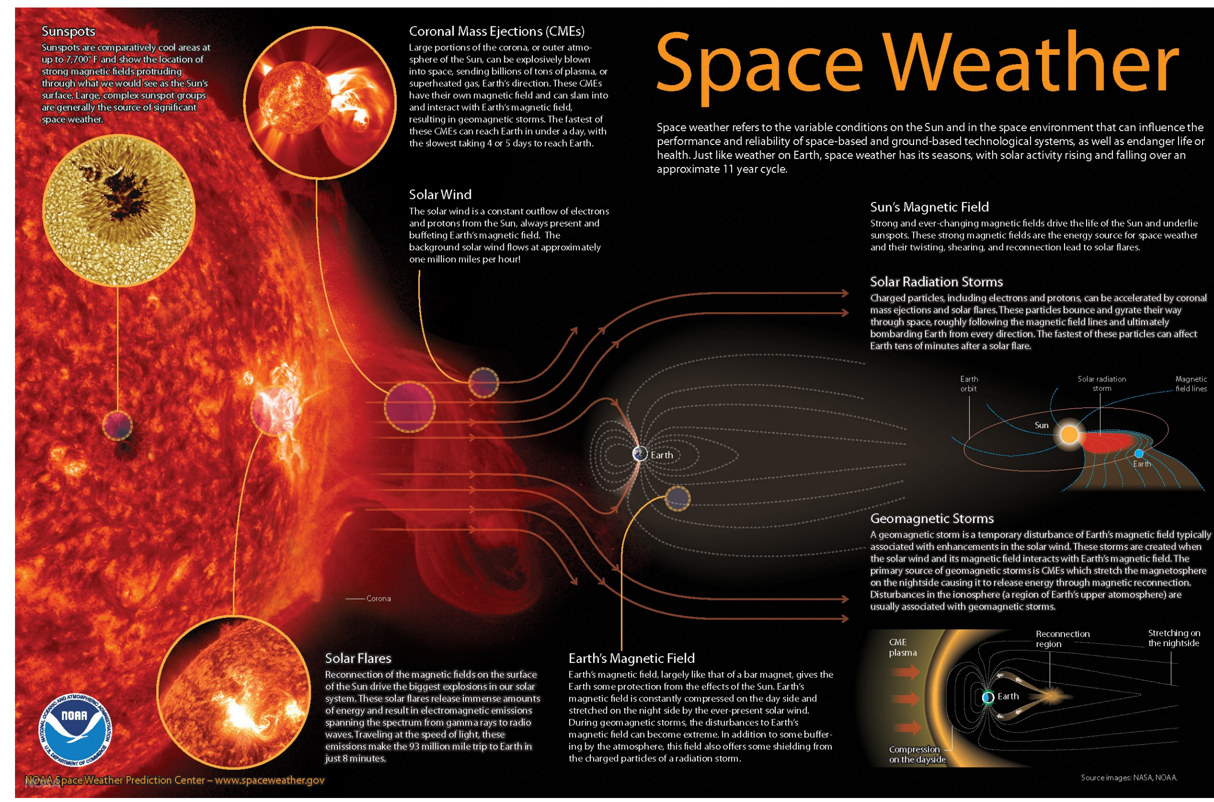
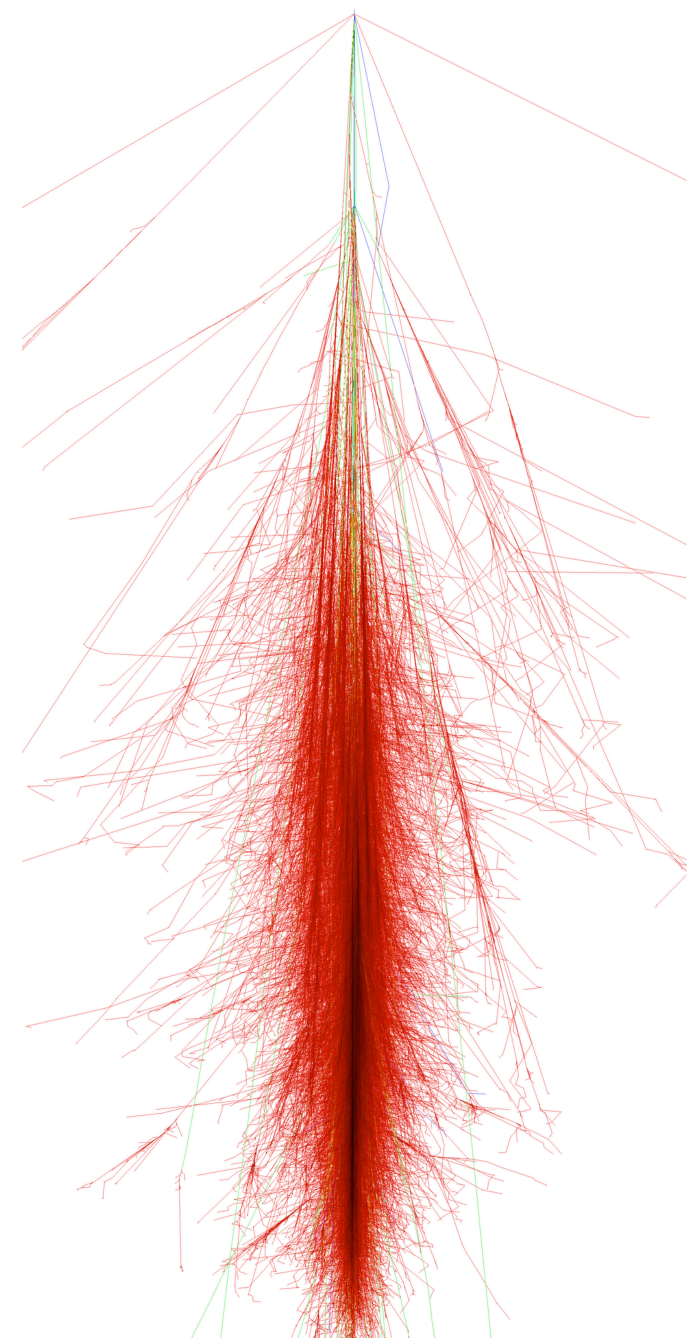
Habitability in the Context of Stellar Activity





Stellar Ionizing Radiation adversely impacts planets

- **Sources: XUV, CME/plasma, Wind/protons, SPE/protons**
- **Planetary effects: Atmospheric escape, alterations in atmospheric chemistry, direct biological damage from radiation**



Atmospheric Escape:A double edged sword

- Protoatmospheres and secondary atmospheres
- XUV-driven hydrodynamic escape
- Energy-limited equation to estimate atmospheric loss
- Comparing the long-term effect of flares and stellar luminosity on planetary atmospheric escape
  (Atri and Carberry Mogan, submitted)

Solar System Planets can be useful

- **Radiation Assessment Detector on the Martian surface (Gale Crater). Great for calibration!**
- **Mars: ~22 g cm^{-2} atmosphere, Earth: 1036 g cm^{-2}.**
- **Numerical model: GEANT4 (for GEometry ANd Tracking) is a platform for "the simulation of the passage of particles through matter” (CERN).**
- **Atmospheric model: Mars Climate Database (MCD).**
- **Galactic Cosmic Rays and SPEs.**

We validate our method by computing the GCR-induced background radiation dose at Gale Crater which has been measured by RAD. We used the BON10 model (O'Neill, 2010) to obtain the background GCR spectrum, with 87% protons, 12% alpha particles and 1% Iron, as a substitute for heavier particles. Our simulations gave the equivalent dose rate from background GCRs to be 0.59 mSv/day, which is consistent with RAD measurement of 0.64 ± 0.12 mSv/day (D. M. Hassler et al., 2014) within instrumental uncertainties. We have also made comparison of our SEP results with similar work on SEPs which is discussed in the next section.

- **SPEs: satellite (PAMELA) + ground-based data (70 major SPEs (1956 - 2006).**
- **(Atri and Dobbs-Dixon, submitted)**

Exoplanets: Atmosphere vs Magnetic shielding

- **Atmospheric depth is a major factor in determining radiation dose on the planetary surface.**

- **Radiation dose is reduced by three orders of magnitude corresponding to an increase in the atmospheric depth by an order of magnitude.**

- **The planetary magnetic field is an important but a less significant factor compared to atmospheric depth.**

- **The dose is reduced by a factor of about thirty corresponding to an increase in the magnetospheric strength by an order of magnitude.**

Atri et al., Astrobiology, 13, 910 (2013)
D. Atri, MNRAS Letters, 465, L34 (2017)
D. Atri, MNRAS Letters 492, L28–L33 (2020)

Radiation Dose on Exoplanets

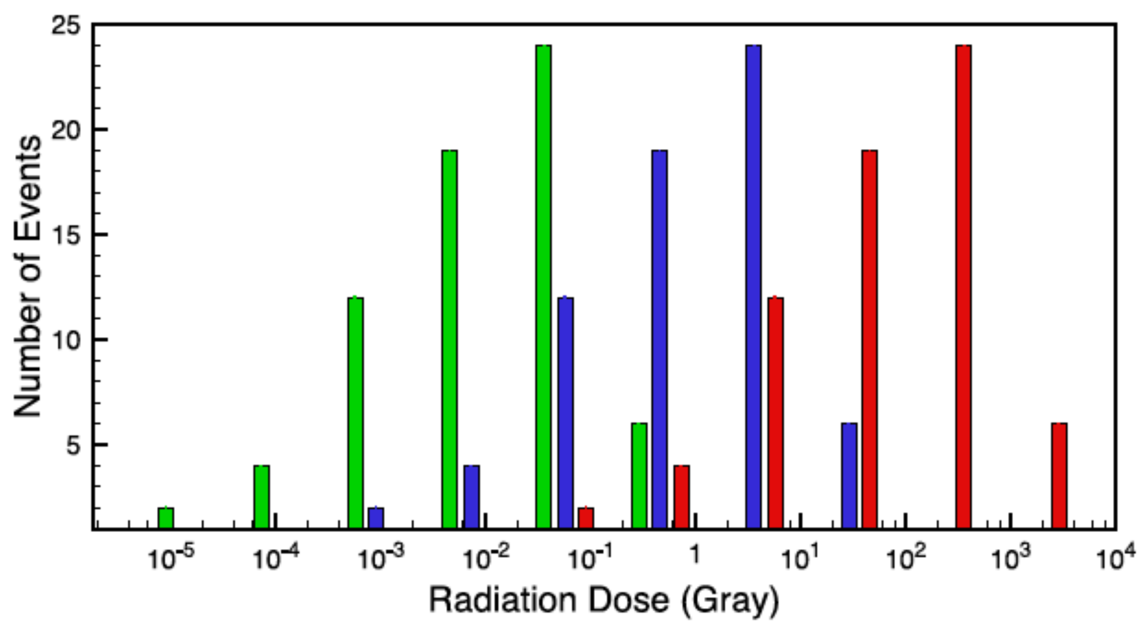


Figure 2. Dose distribution on Proxima b with 30 g cm^{-2} atm and no magnetic field corresponding to 10^{11} (green), 10^{13}* (blue), and 10^{15}* (red) protons cm^{-2} fluence ('∗': linear extrapolation, not observation based).

- **Radiation dose varies significantly with charged particle spectra and an event of a given fluence can have a drastically different effect depending on the spectrum.**
- **Our results show that radiation dose can vary by several orders of magnitude for a given fluence.**

D. Atri, MNRAS Letters, 492, L28–L33 (2020)

Radiation dose enhancement factor

Table 6. Enhancement factor over GCR background on potentially habitable planets for a hard-spectrum event (1998 August 24) with 10^{11} protons cm^{-2} fluence and the Earth's magnetic field. Atmospheric depth varies between 30 and 1000 g cm^{-2}.

	30	100	300	1000
TRAPPIST-1 e	1.35E + 04	1.08E + 04	1.03E + 04	2.19E + 03
TRAPPIST-1 f	7.81E + 03	6.23E + 03	5.97E + 03	1.26E + 03
TRAPPIST-1 g	5.28E + 03	4.22E + 03	4.04E + 03	8.56E + 02
Proxima Cen b	4.57E + 03	3.65E + 03	3.49E + 03	7.40E + 02
GJ 667 C f b	4.41E + 02	3.53E + 02	3.37E + 02	7.15E + 01
GJ 667 C e	2.37E + 02	1.89E + 02	1.81E + 02	3.84E + 01
Kepler-1229 b	1.19E + 02	9.50E + 01	9.09E + 01	1.93E + 01
Kepler-442 b	6.42E + 01	5.13E + 01	4.91E + 01	1.04E + 01
Kepler-186 f	5.76E + 01	4.60E + 01	4.40E + 01	9.33E + 00
Kepler-62 f	2.08E + 01	1.66E + 01	1.59E + 01	3.38E + 00

D. Atri, MNRAS Letters, 492, L28–L33 (2020)

Future outlook

- Planetary habitability: A comprehensive approach with better observations and analyzing all mechanisms is needed.
- Fluence scaling relation (X-ray to pfu) from Herbst et al. (2019)
- Atri, Grenfell, Herbst (in prep.), ETERNAL collaboration