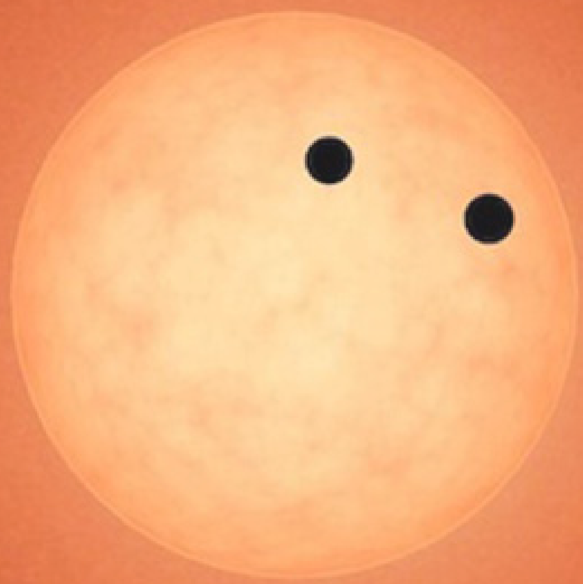

How to Detect IR/Radio Aurorae From an Exoplanet?

Summary from the ExoPlanet Working Group of the 4th Eddy Symposium

January 2024

How to Detect IR/Radio Aurorae From an Exoplanet?

Airapetian, V. S. (NASA/GSFC and American University),
Ankush Bhaskar (ISRO/VSSC, India), Caitlin Gough (University of Leeds, UK),
Meng Jin (LMSAL), Suk-Bin Kang (CUA and NASA /GSFC), Mei-Yun Lin (UC Berkeley, USA), Xudong Sun (University of Hawaii, USA), Vishal Upendran (BAERI and LMSAL, USA)

Planetary aurorae are mostly produced by electrical currents flowing between the ionosphere and the magnetosphere which accelerate energetic charged particles that hit the upper atmosphere.Observations in the radio, ultraviolet (UV), and infrared (IR) bands revealed the signatures of aurorae from magnetized giants including Jupiter, Saturn, Uranus, and Neptune (Zarka 1998; Grodent 2015). Using the Hubble Space Telescope (HST) for morphological observations of the ultraviolet (UV) aurora, and the Cassini Magnetometer (Cassini/MAG) for in situ magnetic field measurements, studies have demonstrated that the primary auroral emissions at Saturn are significantly influenced by the solar wind (Crary et al., 2005) While HST, Voyager II,and recent ground-based observations found a correlation between enhanced solar wind conditions and radio auroral activity from Uranus (Thomas et al. 2023). Thus, observations suggest that planetary aurorae result from a coupling process between an atmosphere and the nearby space environment with the morphology of these aurorae strongly affected by changes in the solar wind [Bunce et al. 2006; Stallard et al. 2007). At Earth, beautiful aurorae glow due to this coupling process between the planet's magnetically controlled region of its atmosphere (magnetosphere) and the magnetized solar wind. Both a southward turning of the interplanetary magnetic field (when the vertical component of the magnetic field is directed southward or in the opposite direction to the northward magnetospheric field which gives rise to magnetic reconnection) and sometimes enhanced solar wind dynamic pressure (the product of the wind density and velocity squared) can drive global auroral brightening events (e.g., Elphinstone et al., 1996; Chua et al., 2001). At Saturn, these processes are collisionally excited (forming UV emission), and ionize H_2 producing to H3+ NIR emission (Stallard et al., 2008).

The discovery of close-in exoplanets with Kepler and TESS has initiated studies to detect H3+ emission in atmospheres of close-in gas giants. The atmospheres of these exoplanets can be impacted by high fluxes of X-ray and EUV emission driving a hydrodynamic escape in the upper atmosphere (Airapetian et al. 2020; Owens 2021). The H3+ emission can cool the upper atmospheres via radiation in the NIR band (at 4 mm) as it does in the atmospheres of Jupiter, Saturn, and Uranus (Lenz et al. 2016). Koskinen et al. (2010) have shown that it can be an efficient coolant even at high temperatures up to 10,000K. Koskinen et al. (2007) estimated a H_3+ NIR emission power at the order of 10^{23} erg/s from HD 209458 suggesting that H_3+ can be efficiently produced in EPGS within 0.1-1 AU, while atmospheres of close-in (at < 0.1 AU) exoplanets will inhibit its production due to thermal dissociation and dissociative photoionization.

Here we propose to study the expected H3+ auroral emission in the atmosphere of DS TucAb, a warm mini-Neptune with a radius of 5.7 ± 0.17 R_E or about 40% larger than Uranus. The planet is located at 0.1 AU from a young (45 Myr old) solar analog, DS TucA, which is 44.1 pc away from the Sun. This is an exceptional target as it is the only nearby young main-sequence solar-like star that generates a high coronal X-ray and Extreme UV flux (~ 10^{30} erg/s), massive winds (>= 10^{-11} solar mass per year) superflares with E > 3 x 10^{33} erg (Carrington type flares) and the frequency of 1 event per 1-2 days (see Fig.1 and Fig 2). Such high fluxes of ionizing radiation will impact the atmosphere of DS TucAb producing a high heating rate that makes it an inflated planet compared to its mass (Benatti et al. 2019). This exoplanetary system is a target of two recent multi-wavelength observational campaigns (PI: Airapetian) using TESS (optical), NICER (X-ray), the Hubble Space Telescope (Far UV), ground-based radio telescopes (ASCAP and MWA) and ground-based spectroscopy. Figure 1 presents the spectral distribution of X-ray and EUV emission from the host star that shows over 4 orders of magnitude enhanced flux incident on the planet as compared to Earth.

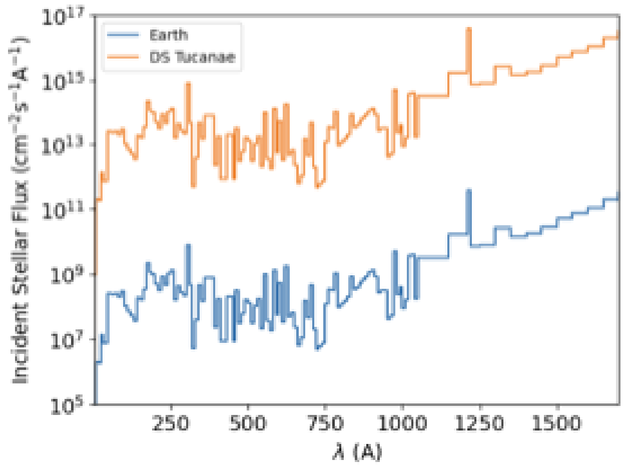

Figure 1. (Top panel)The XUV fluxes at DS TucAb atmosphere, which is 10^5 of the Sun at 1 AU.

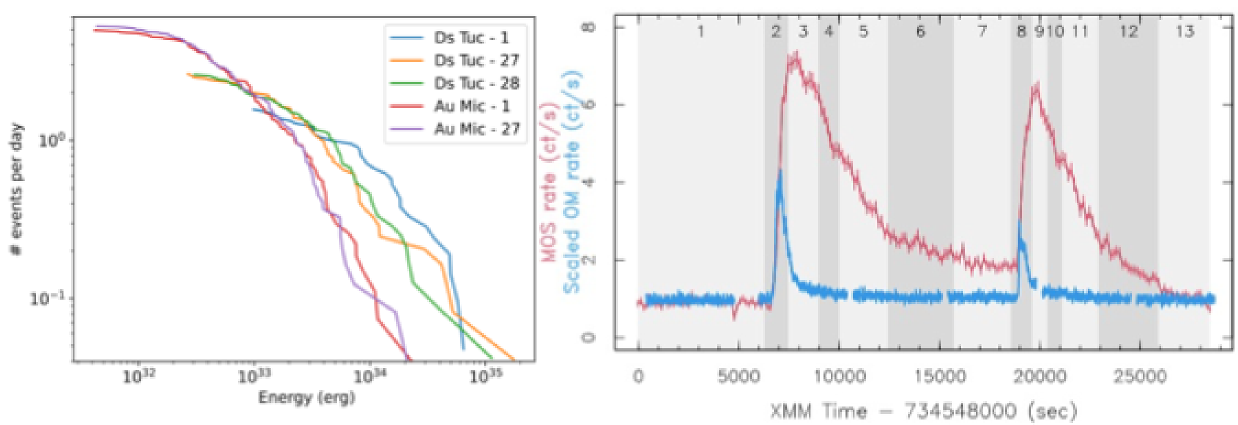

Figure 2. Flares from DS Tuc A: Top- Light curve and superflares of DS TucA as observed by TESS.Left - Distribution of optical superflares observed by TESS [Colombo et al. 2022]; Right – X-ray and UV superflares observed by XMM-Newton [Pilliteri et al. 2022]

Figure 2 shows the flare frequency over energy from DS TucA from TESS data (left panel) and light curves in soft X-rays from XMM-Newton observations (Pilliteri et al. 2022) that suggests that the interaction of a strongly magnetized dense wind from Ds Tuc A with the magnetosphere of the exoplanet Ds TucAb that would be assumed to be comparable of Uranus's produces the compression of the planetary magnetospheric field due to the high stellar wind dynamic pressure, which by a factor of 2 x 10^5 times greater than that experienced by Earth's magnetosphere and 8 x 10^7 times greater than that experienced by Uranus from the solar wind. Also, the strong stellar global magnetic field (1 kG at the surface) should be dragged out to the DS TucAb orbit at 0.014 G (see Fig. 3, an example of the stellar wind from the young Sun, k1 Ceti, Airapetian et al. 2021). This can produce additional heating in the magnetosphere and ionosphere of the planets. The general picture of these processes is depicted in Figure 3.

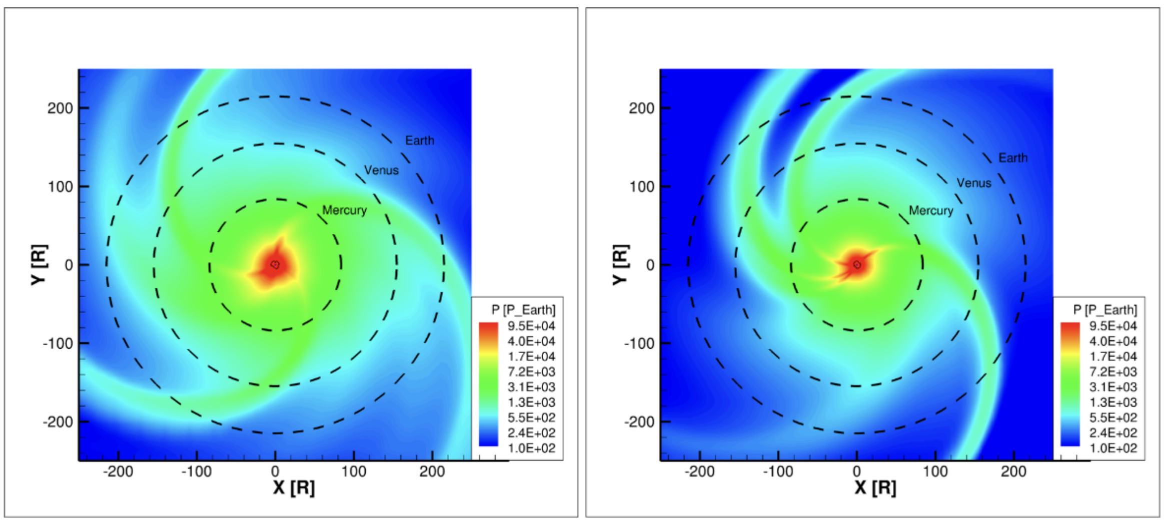

Figure 3. An example of the stellar wind from a young solar analog, k1 Ceti (Airapetian et al. 2021)

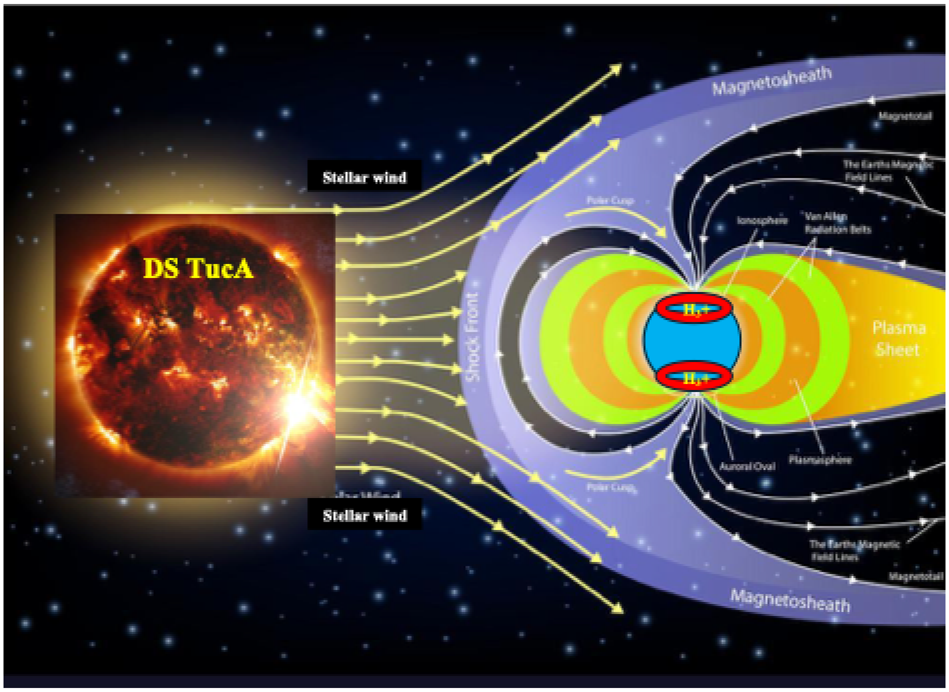

Figure 4. The schematics of the formation of H3+ auroral emission in the atmosphere of DS TucAb.

The objective of the proposed research by our team is to model and to observe aurorae from exoplanets around young solar analogs in radio and IR bands (H3+) or mm-band (H3O+), review open science tools for Exoplanetary space weather characterization, suggest recommendations to make the tools repository more comprehensive and generate a white paper on exoplanetary space weather around DS TucAb.

To calculate the aurora from DS Tuc Ab, a multi-step approach is utilized that integrates advanced public available computational models. First, the stellar wind and stellar CME properties as well as the EUV/X-ray emissions from the star are determined using the 3D global MHD Alfvén Wave Solar Model (AWSoM) within the Space Weather Modeling Framework (SWMF). Following this, the SWMF/BATS-R-US and PWOM will be used to model the interaction of the stellar wind and CMEs with the Ds TucAb's magnetosphere. The final step involves examining whether the electron or particle precipitation fluxes interact sufficiently to produce H3+ ions, a process pivotal for auroral formation using the code H3ppy. By calculating the emission power in the infrared (IR) spectrum, we can quantify the aurora's intensity, offering insights into the energetic processes governing the atmospheric phenomena around DS Tuc Ab.

The impact and relevance of this project are an important contribution of heliophysics tools and methodologies for development of predictive capabilities and future observations of DS TucA and other similar exoplanetary systems with the current observational facilities including James Webb Space Telescope. The identification of auroral emissions from exoplanets represents a significant advancement in our understanding of space weather's effects on these distant worlds. By detecting these emissions in radio and infrared bands, we can begin to quantify the impact of space weather on exoplanets, unraveling how stellar coronae, winds and magnetic fields interact with their magnetospheres and atmospheres. This insight is crucial for assessing the habitability and environmental conditions of exoplanets. Furthermore, the development of a white paper through this project will serve as an invaluable resource, pinpointing the essential open science tools required to delve deeper into the investigation of exoplanetary space weather. This not only fosters a more collaborative and accessible approach to heliophysicists and astrophysicists but also sets the stage for groundbreaking discoveries in the field.

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Relevant Studies and Resources:

1. https://www.nasa.gov/missions/webb/nasas-webb-finds-signs-of-possible-aurorae-on-isolated-brown-dwarf/
2. https://academic.oup.com/mnras/article/494/4/5044/5825375
3. https://ui.adsabs.harvard.edu/abs/2020IJAsB..19..136A/abstract
4. https://github.com/maserlib/ExPRES
5. https://github.com/henrikmelin/h3ppy/tree/master
6. https://emac.gsfc.nasa.gov/
7. https://github.com/storyofthewolf/ExoCAM
8. https://github.com/storyofthewolf/ExoRT
9. https://github.com/NCAR/CESM-planets
10. https://arxiv.org/abs/2309.15239
11. https://www.nature.com/articles/s41550-023-02096-5
12. https://academic.oup.com/mnras/article-abstract/500/4/4818/5986637