A High-Energy View of Exoplanets and their Environments

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ABSTRACT BOOK

Oral Communications and Posters

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Contents

Chapter 1

Invited Speakers

Coronal Mass Ejections and Exoplanets: A Numerical Perspective

Julián D. Alvarado-Gómez[1]
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Flares and coronal mass ejections (CMEs) are more energetic than any other class of solar phenomena. They involve the rapid release of up to 10^{33} erg of magnetic energy in the form of particle acceleration, heating, radiation, and bulk plasma motion. Displaying much larger energies, their stellar counterparts are expected to play a fundamental role in shaping the environmental conditions around low-mass stars, in some cases with catastrophic consequences for planetary systems due to processes such as of atmospheric evaporation and erosion. While flares are now routinely detected in multi-wavelength observations across all spectral types and ages, direct evidence for stellar CMEs is almost non-existent. In this context, numerical simulations provide a valuable pathway to shed some light on the eruptive behavior in the stellar regime. I will review recent results obtained from realistic modeling of CMEs in active stars. Emphasis will be given to M dwarfs, focusing on how the emerging EUV/X-ray/Radio signatures from these events vary as a function of the magnetic properties of the star. I will also discuss our latest simulations of CMEs from the flare star AU Mic, and how these energetic events are expected to affect the two recently discovered exoplanets of this system.

Transiting exoplanets as probes of the stellar and planetary environments

Vincent Bourrier[1]
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Nearly half of the 4500+ known exoplanets orbit within 0.1 au from their star. At such close distances, the nature and evolution of these planets is shaped by interactions with their host star (irradiation, tidal effects, and magnetic fields). In particular, the deposition of stellar X-ray and extreme ultraviolet radiation into an exoplanet upper atmosphere can lead to its hydrodynamic expansion and substantial escape. The resulting extended exospheres are then shaped by the stellar wind and irradiation, and act as magnifying probes of these processes when they transit the star. Through the examples of iconic Jupiter- and Neptune-size planets, I will show the wealth of information that high-energy observations of transiting planets can reveal on both the planetary and stellar atmospheres, and their interactions.

X-ray views of our solar system

Graziella Branduardi-Raymont[1]
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Through observations spanning more than 20 years XMM-Newton and Chandra have provided us with a wealth of X-ray data from the solar system; these have opened a new window on the phenomena taking place in planetary atmospheres and magnetospheres, on minor bodies, and on their response to solar activity.

We are currently in a golden era for joint X-ray and in situ studies of Jupiter, with Juno orbiting the planet and a campaign of multi-wavelength observations taking place simultaneously, with XMM-Newton and Chandra playing prominent roles. Such synergetic measurements have achieved remarkable discoveries and identified emission mechanisms that we expect to see replicated in stellar systems harbouring planets. We then look forward to the time when the next major ESA X-ray observatory, ATHENA, will be flying, and may well do so in synergy with the JUICE spacecraft visiting the Jupiter's system. On a shorter timescale we will witness the impact of the buffeting of the solar wind, and the effects of space weather, on our own planet, by mapping the Earth's magnetosheath and magnetospheric cusps in X-rays with the Soft X-ray Imager on SMILE (Solar wind Magnetosphere Ionosphere Link Explorer), due for launch at the end of 2024.

Exploring Exoplanets and Their Environments with the James Webb Space Telescope

Knicole Colón[1]
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Slated to launch later this year, the James Webb Space Telescope will explore exoplanets and their environments by observing the atmospheres of both transiting and directly-imaged exoplanets at near-to-mid-infrared wavelengths. In this presentation, I will provide an overview of JWST, including its current status, its capabilities for exoplanet observations, and details about the goals and targets of the Early Release Science (ERS) and Guaranteed Time Observations (GTO) exoplanet programs. The ERS and GTO targets notably span a wide range of planet masses and temperatures as well as host star types, which will allow for investigations of how atmospheric properties correlate with planet and stellar properties. Additional General Observer (GO) exoplanet programs proposed by the community were selected for JWST observations in Spring 2021. The GO programs will augment the ERS and GTO programs by providing an even more diverse population of exoplanets to study as well as additional opportunities for comparative science across a range of exoplanet environments. We can ultimately expect to make significant progress in our understanding of the atmospheres of exoplanets and their environments in the era of JWST, especially when coordinated with observations from facilities that operate at complementary wavelength regimes.

Ultraviolet Observations of Exoplanet Host Stars: Recent Results and the Landscape for the Next Two Decades

Kevin France[1], Allison Youngblood[1]
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Ultraviolet spectroscopy is the primary tool for probing the hot atmospheres of cool stars (spectral types F – M). The 10 – 20 nm ultraviolet bandpass contains key diagnostics of the full temperature range from the chromosphere to the corona, is the most sensitive bandpass for stellar flares studies, and can provide direct constraints on stellar coronal mass ejections. After their emission from the star, high-energy photons and particles regulate the atmospheric structure on orbiting planets, influencing the long-term stability of planetary atmospheres and driving atmospheric photochemistry.

In this talk, I will give an overview of recent key results from ultraviolet studies of cool stars (focusing on the extreme ultraviolet bandpass, 10 – 91 nm), with an emphasis on planetary implications, including the production of false positive biomarkers and atmospheric escape. I will conclude by presenting the landscape for stellar and exoplanetary investigations utilizing ultraviolet observations over the next two decades. Missions of all sizes have important roles to play in this area: I will highlight planned or proposed missions ranging from cubesats and smallsats (CUTE, SPRITE, and others) to medium-sized missions (Probe and Explorer class; CETUS and ESCAPE) to flagships (LUVOIR and HabEx).

The end of the worlds

Boris Gaensicke[1]
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Many of the known planets - in the solar system Mars and beyond - will survive the post main-sequence evolution of their host stars into white dwarfs. Later interactions scatter asteroids, moons, and possibly entire planets deep into the gravitational potential of the white dwarf, where they are disrupted by tidal forces. Observational evidence for such evolved planetary systems is ubiquitous in the form of photospheric contamination by planetary material, circumstellar discs, and transits. The study of white dwarfs accreting planetary debris provides insight into the bulk compositions of exo-planets conditions, the efficiency of planet formation around A/F type stars, and the architectures of outer planetary systems inaccessible to direct detections.

CHEOPS: CHaracterising ExOPlanet Satellite -following up on known exoplanets

Kate Isaak[1], the CHEOPS Mission Team[2]
[1] *ESA/ESTEC*
[2] *(including the ESA CHEOPS Project Team and the CHEOPS Mission Consortium)*

The CHaracterising ExOPlanet Satellite is a small (s-class) mission in the Science Programme of ESA, implemented in partnership with Switzerland. Designed to provide ultra-high precision broadband photometry in the 330 - 1100nm waveband, CHEOPS has been in orbit since late December 2019 and is already living up to its potential for follow-up studies of known exoplanets. In this presentation I will give a scientific and technical overview of the mission and its capabilities, highlighting some early scientific results, as well as the opportunity that the mission presents to the Community.

The histories of the young Sun and the Archean Earth's atmosphere

Colin Johnstone[1], Helmut Lammer[2], Kristina Kislyakova[1], Manuel Scherf[2], Manuel Güdel[1]
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The Suns activity and the evolutionary histories of the Earth's atmospheric CO2 and N2 abundances during the Archean eon are by now poorly constrained. We use a state-of-the-art physical model for the upper atmosphere of the Earth to study the effects of different atmospheric CO2-N2 mixing ratios and solar activity levels on the escape of the Earth's atmosphere to space. We find that unless CO2 was a major constituent of the atmosphere during the Archean eon, enhanced heating of the thermosphere by the Sun's strong X-ray and ultraviolet radiation would have caused rapid escape to space. We derive lower limits on the atmospheric CO2 abundance of approximately 40% at 3.8 billion years ago, which is likely enough to counteract the Faint Young Sun Paradox and to keep the Earth from being completely frozen. Furthermore, our results indicate that the Sun must have been born as a slow or moderate rotator to prevent rapid escape, putting essential constraints on the Sun's activity evolution throughout the solar system's history. Our study also has important implications for Earth-like atmospheres on exoplanets orbiting in the habitable zones of (moderately) active stars.

Hot Takes on Highly Irradiated Exoplanet Atmospheres

Laura Kreidberg[1]
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The past 25 years have revealed a diversity of exoplanets far beyond what was imagined from the limited sample in the Solar System, including a large number of highly irradiated planets on short period orbits. The high temperatures of these planets make them ideal targets for atmospheric follow-up characterization. In this talk, I will give an overview of current and future atmosphere characterization efforts for hot transiting planets, with a special focus on how the irradiation environment shapes the planetary climate, atmospheric chemistry and mass loss.

Stellar rotation and its connection to the evolution of hydrogen-dominated atmospheres of exoplanets

Daria Kubyshkina[1]
[1] *Trinity College Dublin*

The population of known low- to intermediate-mass exoplanets shows a large spread in densities, which is believed to be due to the diversity of planetary atmospheres and thus controlled by planetary atmospheric mass loss. One of the main drivers of long-term atmospheric escape is the absorption of high-energy XUV radiation from the host star, and therefore it is intimately connected to the host star evolution. For main sequence solar-like stars, rotation and XUV radiation are closely connected, with faster rotating stars being XUV brighter with both rotation and XUV decreasing with time. This evolution, however, does not follow a unique path, as stars born with the same mass and metallicity can have widely different initial rotation rates. This non-uniqueness holds up to about 1 Gyr, a time before which atmospheric escape from exoplanets is strongest. The atmospheric mass loss through the first Gyr after the protoplanetary disk dispersal is essentially deciding the future of the planet and its position in the observed population. Exploring the connection between the evolution of planetary atmospheres and the evolution of host stars allows us to get insights into both the early history of stars and the primordial parameters of planets.

Star-planet interactions at young ages

Giusi Micela[1]
[1]*INAF -OAPA*

The study of young planetary systems is of great importance for understanding their formation and evolution. Planets do not evolve in isolation but their behavior depends on the host star and the environment in which they are embedded. In particular, at young ages, solar-type stars are much more active than Sun-age stars with all the phenomena that this involve, including strong emission at high energies, from UV to X-rays, stellar winds, flares and CMEs emission.

It is now widely accepted that high energy radiation can drive planetary evaporation, specially of hot low-density planets. It may also have a strong impact on thermal structure and chemical compositions of the atmospheres. X-rays and EUV photons have different roles, since the former produce cascades of secondary electrons, and penetrate deep in the atmospheres, reaching in same cases the planetary surface. Their effects are dependent on metallicity, since they are absorbed mainly from high z elements. On the contrary, the effects of EUV is concentrated on the upper layers of the atmospheres and is fairly independent from metals since EUV is efficiently absorbed by hydrogen and helium. Here I will review some of recent outcomes of star-planet interactions studies during the young stellar ages.

Stellar coronae and the harsh environment where hot Jupiters live

Ignazio Pillitteri[1]
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The X-ray and EUV activity of our Sun has determined important effects on the planets around it. In particular high doses of X-rays, flares, and Coronal mass ejections combined with masses of the planets and the shielding action of the planetary magnetic fields have determined the diverse habitability of rocky planets like Venus, Earth and Mars. In exoplanetary systems the same could apply, especially in those stars with close in planets like hot Jupiters or M dwarfs with Earth analogs. These planets live in the harsh environment of the hot coronal fringes. This has a consequence for the evaporation and the photochemistry of the upper atmospheres of such planets. Furthermore, phenomena related to gravitational and magnetic interaction between stars and close in planets could be at work. Effects due to star-planet interaction could be the transfer of rotational momentum between planet and star, magnetic interaction between the fields of planet and star that could potentially lead to flares in the outer corona, evaporation with the formation of a cloud of planetary gas around the star and accretion onto the star itself. I will report on the search for such phenomena carried on at XUV bands with X-ray observatories like XMM-Newton.

The PLATO Mission

Heike Rauer[1]
[1] *Institute of Planetary Research, DLR*

PLATO (PLAnetary Transits and Oscillations of stars) is the M3 mission of the European Space Agency (ESA) and designed to detect and characterize extrasolar planets. PLATO will provide small planets around bright stars, including terrestrial planets in the habitable zone of solar-like stars. PLATO will characterize these planets for their radius, mass, and age with high accuracy.

PLATO is currently scheduled for a launch date end 2026. Its payload consists of 26 cameras with 12cm aperture each. For at least four years, the mission will perform high-precision, long-term photometric and asteroseismic monitoring of a large number of stars to detect extrasolar planets and derive their radii and ages. The satellite data are complemented by a ground-based observing program to derive the planetary masses.

The missions catalogue of well-characterized small planets at intermediate orbital periods will be an important constraint to planet formation theories and will provide targets for future spectroscopy follow-up observations to characterize planetary atmospheres. These data will be a significant step forward to address the key questions on how planets form and evolve and how frequent rocky planets suitable for the development of life have formed in our milky way.

Searching Near and Far: Transits and Transients from the Transiting Exoplanets Survey Satellite (TESS)

George R. Ricker[1]
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TESS is discovering thousands of exoplanets in orbit around the brightest stars in the sky. This first-ever spaceborne all-sky transit survey has identified planets orbiting a wide variety of host stars, ranging from white dwarfs and M dwarfs, to hot O/B giants. A concurrent TESS ground-based followup program is providing the masses and densities of a large cohort of small planets, including habitable zone rocky worlds.

The initial TESS all-sky survey has been completed, covering 13 observation sectors in the Southern Ecliptic Hemisphere in Year 1, and 13 observation sectors in Year 2. In Year 3, a year-long revisit to the Southern Ecliptic Hemisphere is underway. Concurrent, year long deep surveys by TESS of regions surrounding the North and South Ecliptic Poles are providing prime exoplanet targets for characterization with the Webb Telescope, and for ground-based and space-based telescopes coming online in the next two decades.

Full frame image cadences for TESS were accelerated to 10 minutes commencing in Year 3. In addition, a 20s target cadence was introduced, enhancing detections of stellar flares, short period binaries, asteroseismic oscillations, and recurrent transients.

The status of the TESS mission in its third year of science operations will be reviewed.

The eROSITA mission and its X-ray all-sky survey

Jan Robrade[1]
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eROSITA (extended ROentgen Survey with an Imaging Telescope Array) is the primary instrument on the Spectrum-Roentgen-Gamma (SRG) mission. The SRG spacecraft was launched on July 13, 2019 and placed in an L2 halo orbit. After a calibration and performance verification phase of the instruments, the eROSITA All-Sky Survey (eRASS) started in December 2019. The eROSITA all-sky survey has a duration of four years consisting of eight all-sky scans and covers the 0.2-10 keV X-ray energy band.

The eRASS will be at soft X-ray energies about 25 times more sensitive than the ROSAT All-Sky Survey and provides enhanced positional accuracy and spectral resolution. The survey will revolutionize our view of the high-energy universe and provides new insights into a wide range of astrophysical phenomena. Already now eROSITA has detected about one million X-ray sources in its survey, a fraction of about 20 percent of these are stellar sources. I introduce the eROSITA/SRG mission and present first results from eROSITA with a focus on stellar and exoplanetary science.

Measuring the Magnetic Fields of Exoplanets with Star-Planet Interactions

Evgenya Shkolnik[1]
[1]*Arizona State University*

Planets interact with their host stars through gravity, radiation and magnetic fields. For giant planets orbiting stars within ~20 stellar radii (=0.1 AU for a Sun-like star), magnetic star-planet interactions (SPI) are observable at a range of wavelengths with a variety of photometric, spectroscopic and spectropolarimetric techniques. At such close distances, planets orbit within the sub-alfvénic radius of the star, where magnetic interactions are particularly efficient, allowing for the detection and study of exoplanetary magnetic fields, thus probing their internal dynamics and atmospheric evolution. In this talk, I will provide a review (and preview) of magnetic SPI studies for hot Jupiters orbiting Sun-like stars. As we refine our observational techniques, we can extend them to lower-mass stars where the sub-alfvénic region coincides with the classical habitable zone, giving us a way with future experiments to detect the magnetic fields of potentially habitable planets.

Chapter 2

Exoplanets Atmospheres

Analysis of X-ray driven atmospheric loss on three-planet system K2-136

Jorge Fernandez Fernandez[1], Peter Wheatley[1]
[1] *University of Warwick, Coventry, UK*

I will present XMM-Newton observations of K2-136, a K-dwarf member of the Hyades cluster, which has an age of 600 Myr. The star hosts three transiting planets, with radii of 1.0, 3.2 and 1.5 Earth radii (in order of orbital separation). The survival of the gaseous envelope of the sub-Neptune is intriguing, given that it lies between two relatively volatile-poor planets.

While the precise X-ray irradiation history of the system may be uncertain, the three planets must have shared the same history. I will discuss the estimated X-ray driven atmospheric loss of these planets, as well as their likely irradiation history, and consider their future evolution. The system provides an excellent opportunity to compare the atmospheric evolution of a range of exoplanets in a shared X-ray environment.

Sculpting the sub-Saturn Occurrence Rate via Atmospheric Mass Loss

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The sub-Saturn (4-8 $R_\oplus$) occurrence rate rises with orbital period out to at least $\sim$ 300 days. In this work we adopt and test the hypothesis that the increase in occurrence with period is a result of atmospheric mass loss, which can transform sub-Saturns into sub-Neptunes more efficiently at small periods. We show that the orbital period distribution can be leveraged to infer the core mass function of sub-Saturns. Because sub-Saturns and giant planets likely share the same core formation channel, our constraints on the sub-Saturn core mass function may extend to giant planets. We find that lognormal core mass functions peaked between $\approx 10-20$ $M_\oplus$ are compatible with the data. Our model predicts that $\sim$ 5 percent of the sub-Neptunes (<4 $R_\oplus$) between orbital periods 4-20 days are evaporated sub-Saturns. Our results can be directly tested with more radius, mass, and period measurements of sub-Saturns.

Effect of Stellar Coronal Mass Ejections (CMEs) and Flares on the atmosphere of HD189733b and its transit signature

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The evolution of planetary atmospheres is very much dependent on the environment of their host stars (e.g., stellar radiation, stellar wind, stellar flares and Coronal Mass Ejections (CMEs)). For close in planets, the stellar radiation evaporates the planetary atmosphere as a form of supersonic planetary outflow due to photoionisation. The interaction of stellar wind with this planetary outflow helps to shape up the atmosphere and its mass loss rate. Moreover, flares and CMEs from the star will also have great impact on planetary evaporation. In this work, we investigate the impact of flares and CMEs on the atmosphere of the exoplanet HD189733b. We solve mass, momentum and energy equations in 3D including ionisation rate equations to launch the planetary wind self-consistently. As we solve extra photoionisation equations, we can calculate the hydrogen ionisation fraction properly. We study four cases: first - the quiescent phase of the star including stellar wind, second- a flare case, third- a CME case and fourth- the flare is followed by a CME. We calculate transit lines for each case. We find that the flare case and CME case have a significant effect on mass loss rate of the planets and hence on their transit lines.

Estimating the atmospheric mass loss of V1298 Tau's four young planets and the role of the host star in planet population studies

Laura Ketzer[1], Katja Poppenhaeger[1], Matthias Mallonn[1]
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Kepler observations revealed two striking features in the distribution of exoplanet radii: a dearth of short period sub-Neptune-sized planets, and a gap around 2 $R_\oplus$. Atmospheric escape of planetary H/He envelopes driven by the high-energy (XUV) radiation from the host star can explain the presence of the desert and radius valley. The very young ($\sim$25 Myr) V1298 Tau system with its four Neptune- to Jupiter-sized planets is an excellent system to test planet formation and evolution models. To investigate the fate of the planets, we obtained X-ray measurements of V1298 Tau with Chandra, and calculated the photoevaporative mass loss rates using PLATYPOS, an open-source tool to model the (energy-limited) atmospheric escape of planetary systems. We allowed for the host star to spin down at different ages, which translates into a low, intermediate, and high activity stellar evolutionary track. Our findings show that in certain planetary-mass and orbital-distance regimes, the stellar high-energy evolution determines if a planet is stripped completely or can retain some fraction of its initial gaseous envelope. We expand on this work by investigating the influence of the host star on the outcomes of planet population studies, in particular when including a realistic distribution of stellar activity tracks.

Helium observations of exoplanet atmospheres are connected to stellar coronal abundances

Katja Poppenhaeger[1]
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Transit observations in the helium lines near 10830 Angstrom are a new successful tool to study exoplanetary atmospheres and their mass loss. Forming those lines requires ionization and recombination of helium in the exoplanetary atmosphere. This ionization is caused by stellar photons in the extreme UV (EUV); however, no currently active telescopes can observe this part of the stellar spectrum. The stellar spectrum close to the helium ionization threshold consists of individual emission lines, many of which are formed by iron at coronal temperatures. Coronal elemental abundances exhibit distinct patterns related to the first ionization potential (FIP) of those elements, with elements like iron being strongly depleted for high-activity low-mass stars. I show that stars with high versus low coronal iron abundances follow different scaling laws that tie together their X-ray emission and the EUV flux close to the helium ionization threshold. I also show that the currently observed large scatter in the relationship of EUV irradiation with exoplanetary helium transit depths can be reduced by taking coronal iron abundances into account, allowing us to target exoplanets with well-observable helium signatures with much higher confidence.

The high energy environment and atmospheric behavior of K2-25b

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[6] *Department of Astronomy, Columbia University, New York, US*

K2-25b is a Neptune-sized exoplanet (3.45 Earth radii) that orbits its M4.5 host with a period of 3.48 days. The system resides in the young Hyades Cluster (680 Myr). K2-25b's youth and its similarities with Gl 436b suggest that K2-25b could be undergoing strong atmospheric escape. We observed two transits of K2-25b at Lyman-alpha using HST/STIS to search for escaping neutral hydrogen. We find that $R_p/R_\star < 0.99$ (0.48) at 95% confidence by fitting the light curve of the Lyman-alpha blue-wing (red-wing). We reconstructed K2-25's intrinsic Lyman-alpha profile, finding the Lyman-alpha flux to be $2.17^{+0.46}_{-0.47}$ erg s^{-1} cm^{-2} at 1 AU from the star. We fit a one-temperature collisionally-ionized gas model to an XMM-Newton spectrum and determined the X-ray flux at 1 AU to be $5.88^{+1.16}_{-0.56}$ erg s^{-1} cm^{-2}. Based on the large XUV flux, we estimated the maximum energy-limited mass loss rate of K2-25b to be 11.8×10^{10} g s^{-1}, five times larger than the mass loss rate of Gl 436b. A non-detection of a Lyman-alpha transit could be due to, e.g., atmosphere composition or the system's youth. A possible scenario is that the high energy environment ionizes the planetary upper atmosphere, making it unable to interact with Lyman-alpha photons.

Photoevaporation vs. Core-Powered Mass-Loss

James Rogers[1], James Owen[1]
[1]*Imperial College London*

The bimodality in the size of small, close-in exoplanets is one of the most intriguing observational features to be discovered in the exoplanet population. Two of the most popular models to explain this, namely Photoevaporation and Core-Powered Mass-Loss, suggest that exoplanets may lose their primordial hydrogen dominated atmosphere and transition from a sub-Neptune to a super-Earth, leaving a sparsity of planets around 1.8 Earth radii. However, these models propose different driving mechanisms for such atmospheric mass-loss, with photoevaporation invoking stellar EUV/X-ray irradiation and Core-Powered Mass-Loss invoking remnant thermal energy in the planetary core. As a result, the two models predict differences in how they behave with varying stellar mass. In this work, we exploit this fact and present a new method for finding signatures in demographic surveys to determine which of these two models is the driving mechanism in producing the bimodality in exoplanet radii. Finally, we predict the size and style of a survey required to distinguish between Core-Powered Mass-Loss and Photoevaporation.

X-exoplanets coronal models and planet photoevaporation

Jorge Sanz-Forcada[1]
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High energy emission photons in the X-rays and EUV bands ionize H and other atoms, posing a thread for the stability of the atmospheres of short period exoplanets orbiting late type stars. Effects such as planet atmospheric evaporation are being attributed in the last years to XUV stellar irradiation on the planets. Early theoretical works tried to model how would the XUV emission affect the planetary atmospheres, mainly by using the solar emission as a scaled pattern. In X-exoplanets (Sanz-Forcada et al. 2010, 2011) we reported for the first time the use of coronal models based on actual data from the exoplanet host stars. The use of coronal models allow us to model the SED of the XUV emission of these stars, otherwise inaccessible to current telescopes. Along this talk I will present the use of these models with datasets of different data quality, depending on the availability of low or high spectral resolution spectra in both X-rays and UV. Comparison with actual data will be shown for exoplanet host stars such as Proxima Cen or AU Mic. The challenges for the future use of coronal models in exoplanet atmospheres will be discussed.

Using Lyman-Alpha transits to provide insight into atmospheric escape

Ethan Schreyer[1], James Owen[1]
[1]*Imperial College*

Planets with extended hydrogen/helium atmospheres orbiting close to their parent stars are prime candidates to be observed with escaping atmospheres by Lyman Alpha transit spectroscopy. For certain systems, this spectrum shows significant absorption at velocities greater than 70 km/s however simulations indicate that the speed of hydrodynamic outflows from these planets can only reach around 10 km/s. The most prominent explanations to explain this difference is that the outflowing hydrogen atoms are accelerated by interactions with the stellar wind and radiation pressure. These theories are successful in reproducing observations for specific systems, however work needs to be done to explore this over a large range of different system parameters. My poster will discuss my ongoing PhD project which aims to examine the the interaction between the stellar wind and a planetary outflow in a 3D hydrodynamic framework and understand the implications for observations over a large parameter range.

Radiation-Hydrodynamic multi-species escape from Hot Jupiters

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Photoevaporative models are an important tool for helping to understand the radius distribution of exoplanets. So far, those models have often focused on the escape of H/He mixtures, neglecting coupled escape with heavier species, or assumed a fixed hierarchy of major and minor species. In this work, we relax those assumptions by using a truly multi-species simulation framework, including radiation transport and friction. We present a set of tentative results aiming at understanding the behaviour of solutions we find for Hot Jupiter exoplanets. This will open the path for the investigation of other classes of exoplanets in the near-future.

Chapter 3

Stellar Magnetic Activity

Starspot modulation and flares of M dwarfs with habitable zones accessible to TESS

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I present an analysis of starspot modulation and flares in the TESS lightcurves of 112 M dwarfs with a TESS magnitude $\leq$11.5 that are listed in the TESS Habitable Zone Star Catalog (HZCat, Kaltenegger et al. 2019). Understanding the magnetic activity of these potential exoplanet host stars is crucial for planet characterizations since an active, flaring host star might impact planetary habitability. Our sample is of particular interest as it comprises stars in the HZCat with sufficiently long TESS observation times for planets to be detected in the entire habitable zone. We detected more than 2000 optical flares in this sample and I discuss the relation of flares with spectral type and rotation period. I also present flare frequency distributions and the flux reaching the habitable zone during flare events. I used the results of simultaneous XMM-Newton and K2 flare observations in the Pleiades presented by Guarcello et al. (2019) to estimate X-ray flare fluxes on the basis of optical observations.

A deep learning approach to understand solar/stellar XUV activity

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Stellar X-rays and extreme ultraviolet (XUV) activity is responsible for driving hydrodynamic loss processes in planetary atmospheres. However, due to interstellar absorption direct observations of the full XUV spectrum in cool stars are rare, and we are heavily reliant on empirical models. We propose an alternative approach to tackle this problem, where we use an artificial neural network based deep learning framework to simulate the full solar/stellar XUV spectrum. Our neural network model is trained on thousands of solar spectrum and the simulations are in very strong agreement with observations. In this presentation I will talk about our neural network model, preliminary results, and its future extension to stellar XUV modelling.

STAR-MELT: STellar AccRetion-Mapping with Emission Line Tomography

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Accretion is a fundamentally important process for pre-main-sequence stars, affecting disk stability and evolution, stellar rotation and activity, and planet formation and migration. The main observational challenge is probing the sub-au scales of the innermost disk, not yet possible via interferometry. Such young stars, however, possess a wealth of high-energy emission lines, revealing the nature of these accretion-related processes.

We have developed the Python package STAR-MELT to automatically extract, identify, and fit emission lines, directly from the input data. These lines can then be used to investigate the magnetospheric accretion and its temporal variability; allowing us to tomographically map the accretion structures and inner disk of the PMS stars.

Following our accepted XMM-Newton proposal, HERA: High-Energy Radiation from Accretion in young stars, we will be expanding the compatibility of STAR-MELT to include these high energy emission lines in the x-ray. HERA will observe two of the prototypical YSO monitoring targets from the HST ULLYSES program, simultaneously with HST. These data will provide a unique look at accretion and magnetic activity across the energy regimes. STAR-MELT will facilitate these analyses, allowing for temporal comparisons across the different energy ranges.

The X-ray activity cycles of young solar-like stars

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The 3-yr X-ray activity cycle of the 500 Myr-old solar-like star ϵ Eridani, revealed by *XMM-Newton*, defines at which age and at which activity level coronal cycles set in. Interestingly, ϵ Eridani has the same age as our Sun when life started to develop on Earth. Throughout a cycle, magnetic structures rise to the stellar surface, evolve and decay. These structures are spatially unresolved with present-day X-ray instruments on stellar coronae. I present a new method that reproduces the stellar X-ray spectrum and its variability with solar magnetic structures. The technique converts solar corona observations into a format virtually identical to stellar X-ray observations and, specifically, *XMM-Newton* spectra. From matching these synthetic spectra with those observed for ϵ Eridani, a fractional surface coverage with solar magnetic structures can be associated to each state of its activity cycle. We found that even during the cycle minimum a large portion of ϵ Eridani's corona is covered with active structures. Therefore, there is little space for additional magnetic regions during the maximum, explaining the small observed cycle amplitude in terms of the X-ray luminosity. I also present preliminary results from the application of this method to the even younger star Kepler63 (210 Myr).

X-ray Super-Flares From Pre-Main Sequence Stars: Energetics, Frequency, Loop Geometry, Comparison With Solar Flares

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The most powerful flares from pre-main sequence stars (PMS), super-flares (SFs), have total energies $10^{34} - 10^{38}$erg. Among >24,000 young (t<5Myr) X-ray stars emerged from our Chandra MYStIX/SFiNCs surveys, we identify and analyze 1,086 X-ray SFs, the largest sample ever studied. We find: 1) X-ray SFs are produced by young stars of all masses over a range of evolutionary stages from protostars to diskless stars with the occurrence rate positively correlated with stellar mass. 2) A powerlaw slope in the flare energy distributions is consistent with those of optical/X-ray flaring from older stars. 3) SFs alone may speed up the processes of gas photoevaporation in disks and planets by 10-20% assuming a linear response of disks/atmospheres to flare events. We fit plasma models to the 55 brightest X-ray SFs and compare them with published SFs from young ONC and older stars. 4) The properties of PMS SFs are independent from the presence or absence of protoplanetary disks. 5) A new correlation of loop thickness or geometry is linked to stellar mass. 6) The slope of a long-standing relationship between the X-ray luminosity and magnetic flux of various solar-stellar magnetic elements appears steeper in PMS SFs than for solar events.

XUV Activity Evolution of Main-Sequence Stars and its Relevance for Habitable Planets

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Planetary atmospheric evolution is partly driven by the host star's ultraviolet-to-X-ray (XUV) radiation inducing ionisation, heating, and chemical reactions; substantial atmospheric mass loss can be a consequence of XUV irradiation, thus critically determining the fate of an entire atmosphere. Modeling studies therefore require knowledge of the XUV activity evolution of host stars; this evolution is highly non-unique during the first ~Gyr in the lives of cool main-sequence stars because of the non-unique initial stellar rotation rates. We present a comprehensive model supported by large observational data sets to describe the ensemble of pathways of XUV/rotational evolution of stars with masses of 0.1-1.2 $M_{\odot}$, thus including fully convective M dwarfs, for ages between a few Myrs and 5 Gyrs. We will show that as a consequence of both spin-down and bolometric evolution, the XUV fluxes in the habitable zones (assuming HZ boundaries at 5 Gyr) are at all ages higher for lower-mass stars. We will highlight the crucial extreme-ultraviolet radiation, its spectrum in the context of the X-ray spectrum, the contribution of X-ray flares, and the Ly-α emission line. Our XUV and rotational evolution tracks are useful for application to thermochemical and hydrodynamic models of upper atmospheres of terrestrial planets.

Giant white-light flares on fully convective stars occur at high latitudes

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Small, fully convective stars produce intense flares that indicate strong stellar magnetic fields and shape the environments of exoplanets in their orbits. How these fields are produced is still unclear, since the solar-like magnetic dynamo requires a star to have a radiative core which is missing in these stars, and alternative dynamo models still struggle with reproducing the observables of fully convective stars. In a systematic analysis of fully convective stars observed with TESS, we detected four stars that displayed giant flares which were modulated in brightness by the stars' rapid rotation. The exceptional morphology of the modulation allowed us to directly localize these flares between 55° and 81° latitude on the stellar surface, while flares on the Sun typically occur at much lower latitudes below 30°. Our results imply that strong, dynamic magnetic fields emerge close to the rotational poles in fully convective stars. We show that planets that orbit these stars may be exposed to different amounts of radiation and particles depending on the tilt of the orbital plane with respect to the stellar rotation axis.

Bright in the UV but Faint in X-rays: Young Late-type Stars, or Main Sequence Imposters?

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Newly released Gaia data provide an opportunity to identify and study young, low-mass stars within 100 pc of our solar system. Such stars provide unique insight into the early evolution of stars and planetary systems. Recent searches have revealed an interesting problem, however: a subset of candidate young K and early-M stars with UV-bright chromospheres, identified via Gaia-based color-magnitude diagrams, display kinematics that are discordant with their young (< 100 Myr) isochronal ages. Furthermore, a significant fraction of these young star candidates appear to have unusually low X-ray luminosities. Many were undetected in the ROSAT All-sky Survey (RASS), despite their proximity (distances < 50 pc). Even if these are in fact main sequence stars with magnetically/rotationally inflated radii, the question would remain as to why they appear to lack coronal activity. To address this puzzle, we are obtaining Chandra X-ray imaging spectroscopy of a sample of overluminous, UV-bright stars within 30 pc of the Sun for which RASS data indicates $\log{(L_X/L_{\rm bol})} < -4.5$. We will present initial results from this Cycle 22 Chandra observing program to shed light on (a) why some pre-main sequence stars are main sequence imposters and (b) lack vigorous cornea despite displaying other indicators of stellar magnetic activity.

Probing activity and rotation of M dwarfs with X-rays and photometric timeseries

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Magnetic activity is an important driver for the evolution of planetary atmospheres, especially for M dwarfs which have close-in habitable zones strongly exposed to high-energy radiation. Yet their X-ray activity level, its connection with optical activity and other stellar parameters such as rotation and mass are poorly understood.

The X-ray activity / rotation relation is a key diagnostic to examine these connections. However, the number of M dwarfs with sensitive X-ray and rotation measurements has for a long time been very limited. New XMM-Newton and Chandra X-ray observations and K2 mission rotation periods (Prot) analyzed in my PhD project have substantially increased the number of low activity and slow rotation stars that have been difficult to assess in the past. Combining the new data with a systematic revision of literature data I have examined the activity-rotation relation in different mass bins within the M dwarf regime. Several interesting findings emerged that I will discuss. Combining our observational Lx-Prot analysis with spin-down models we constructed an Lx-age relation for M dwarfs and compared it to observations, including known planet hosts. I will also present the first results from an extension of this work using eROSITA X-ray observations and TESS rotation periods.

An Updated X-ray Activity-Rotation Relation in Low-Mass Stars in Praesepe and the Hyades

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Low-mass stars are known to be magnetically active for a large fraction of their long main-sequence lifetimes. An important manifestation of this activity is their coronal X-ray emission, which can significantly impact any planets they host. Characterizing this emission, its dependence on stellar rotation, and how the two evolve, is one of the keys to determining the radiation environment in which exoplanets exist. Most activity-rotation studies include stars with and without accurate ages, hindering us from disentangling evolutionary signatures in this relation. Furthermore, studies of the activity-rotation relation often interpolate between the properties of stars in the nearby, coeval open clusters Hyades and Praesepe, and those of the Sun. We present extensive catalogs of X-ray detections for low-mass members of the Hyades and Praesepe using observations from Chandra, ROSAT, Swift, and XMM-Newton, thereby characterizing coronal activity at $\approx$700 Myr. We combine these data with rotation periods for the same stars obtained primarily from K2 to analyze the activity-rotation relation for these benchmark clusters. Our efforts to establish these two clusters as secure benchmarks in the study of the activity-rotation in low-mass stars will help to constrain the evolution and current habitability of exoplanets.

Simultaneous multi-wavelength observation of flares on highly active M dwarf: EV Lacerate

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We acquired data of nearby dM3.5e star EV Lac using 5 different observatories: NASA's TESS mission, NASA's Neil Gehrels Swift Observatory (*Swift*), NASA's Neutron Interior Composition Explorer (NICER) and two ground based telescopes (University of Hawaii 2.2-m (UH88) and Las Cumbres Observatory Global Telescope (LCOGT) Network), to span a comprehensive, simultaneous wavelength coverage of flaring events. We identified 56 flares in the TESS light curve, 9 flares in the *Swift UVM2* light curve, 14 flares in the NICER X-ray light curve, and 1 flare in the LCOGT light curve. However, we did not identify flares in the *Swift* XRT light curve or UH88 spectrum. We compare flare frequency distribution (FFD) of flares observed by TESS, NICER and *Swift*/UVOT. We find that the FFDs of TESS and NICER flares have comparable slopes, β_T = -0.67±0.09 and β_N = -0.64±0.19, and that the FFD of UVOT flares has a shallower slope (β_U = -0.38±0.13). Our results will be useful to model and estimate the impacts of strong flares on the atmospheres of planets orbiting M dwarfs.

The Far Ultraviolet M-dwarf Evolution Survey: The Rotational Evolution of High-Energy Emissions

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M-dwarf stars are prime targets for exoplanet searches because of their close proximity and favorable properties for both planet detection and characterization. However, the potential habitability and atmospheric characterization of these exoplanetary systems depends critically on the history of high-energy stellar radiation from X-rays to NUV, which drive atmospheric mass loss and photochemistry in the planetary atmospheres. With the Far Ultraviolet M-dwarf Evolution Survey (FUMES) we have assessed the evolution of the FUV radiation, specifically 8 prominent emission lines, including Lyα, of M-dwarf stars with stellar rotation period and age. The luminosity evolution with rotation of these spectroscopic features is well described by a broken power-law, saturated for fast rotators, and decaying with increasing Rossby number, with a typical power-law slope of -2. Our analysis of the UV luminosity evolution with age further shows that habitable zone planets orbiting lower-mass stars experience much greater high-energy radiative exposure relative the same planets orbiting more massive hosts. Around early-to-mid M-dwarfs these exoplanets, at field ages, accumulate up to 10-20× more EUV energy relative to modern Earth. Moreover, the bulk of this UV exposure likely takes place within the first Gyr of the stellar lifetime.

Rapidly Rotating Pre-main-sequence M Dwarfs with Highly Structured Light Curves

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In recent years, we have been using K2's high precision photometry to probe stellar variability and stellar rotation to lower masses and lower amplitudes than has ever been done before. We find a new type of periodic photometric variability among rapidly rotating (¡0.6d) young (¡50 Myr) M stars without IR excesses. The variations are too sharp and narrow to be due to spots, and too broad to be planets. We think this is likely due to matter entrained in coronal loops. This poster will present new results from our TESS study of stars in the 15 Myr old Upper Centarus-Lupus (UCL)/Lower Centaurus-Crux (LCC) association.

X-ray emission from ultracool dwarfs

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In the predominantly neutral photospheres of ultracool dwarfs (UCDs; spectral type M7 and later) magnetic field and matter are expected to show poor coupling. This should be shutting off magnetic activity. Nevertheless, radio, Halpha and X-ray emission has occasionally been observed from UCDs.

The most peculiar feature in the UCD multi-wavelength characteristics is their radio/X-ray dichotomy: (a) X-ray flaring objects tend to be radio-faint and (b) radio-bursting UCDs are mostly undetected in the X-ray band. The coronae of UCDs may thus represent a transition between solar-like 'normal' magnetic fields (group a) and planetary-like magnetic structure (group b).

Thanks to transit missions which are boosting the detections of planets around small stars, UCDs have recently also come into focus as planet hosts. Measuring the high-energy flux in their surroundings and the amount of its variability is therefore of prime interest for habitability.

I will present several ongoing projects to characterize the coronal activity of UCDs. These studies include (i) joint XMM-Newton / JVLA observations to examine the radio-X-ray relation, (ii) the detection of an X-ray super-flare on an L dwarf, (iii) new X-ray detections from a cross-match of Gaia and XMM-Newton archival data, and (iv) first results from the eROSITA mission.

The Orion Radio All-Stars: High-energy processes in YSOs with the VLA, ALMA and the VLBA

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We are presenting unprecedented new insights into the radio time-domain of YSOs, starting with a follow-up of our deep VLA radio survey in the central part of the ONC at cm-wavelengths, now expanded to the outskirts of the cluster and revealing hundreds of young stars, proper motions, and variability. Radio variability in protostars at these wavelengths is associated with nonthermal (gyro-)synchrotron emission from magnetospheric activity and thus, together with thermal X-ray emission from heated plasma, probes the high-energy processes in YSOs. We additionally expand our study of nonthermal YSO radio variability using ALMA (mm-wavelengths) and the VLBA (cm-wavelengths), both with unprecedented sample sizes. The millimeter range allows us to constrain the occurrence of synchrotron flares which could have an impact on planet formation in circumstellar disks as well as implications for disk mass measurements of insufficiently resolved proplyds. On the other hand, the VLBA allows us to filter out any thermal emission making possible the study of exclusively nonthermal emission, which can be studied without complicated time-sliced imaging. Overall, we find strong evidence of the effect that high-mass stars in the Trapezium have on the radio properties of nearby sources which most likely show free-free radio emission from external photoevaporation.

Chapter 4

Star-Planet Interations

Role of Star Planet Interactions in the Observed X-Ray Activity of HD179949

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We analyse the X-ray coronal data of HD179949, a Sun-like star with a close Jupiter-mass planet. We investigate the Star-Planet Interaction (SPI) effect that has been detected intermittently in the chromosphere. We perform spectral fitting on archival Chandra data and measure the abundances of several metals like Al and Fe are found to have abundances 1.1 and 0.3 times the solar abundance, while Si and Mg have an abundance of 0.5 times the solar abundance. Further, we are able to model the observed spectrum with a two-component APEC model, and obtain consistent abundance measurements over several phases. We use data from Chandra along with data from Swift and XMM-Newton to calculate the variation of X-ray flux versus phase to study the detectability of the SPI, which Scandariato et al. 2013 suggested is obscured by other signatures. We also find evidence for short term variability in spectral hardness, which we attribute to the evolution of the stars active regions.

Star-planet Interactions in AU Mic b: High Energy Irradiation vs Strong Stellar Winds

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The high-energy flux in X-ray and Extreme ultraviolet that young close-in planets receive from their host stars can lead to strong atmospheric evaporation. For these planets, their atmospheres take the form of dense photoevaporative hydrogen outflows. The stellar wind exerts pressure on the expanding atmosphere and, if sufficiently strong, can affect atmospheric escape rates and spectroscopic transit signatures. We study the dichotomy of the escaping atmosphere of the newly discovered close-in exoplanet AU Mic b. The high EUV stellar flux is expected to cause strong atmospheric escape. However the wind of this young star is also believed to be very strong, which could reduce or even inhibit the planet's atmospheric escape. Through 3D hydrodynamic simulations, we show that, as the stellar wind becomes stronger, the evaporation rate of AU Mic b is reduced and its atmosphere is forced to occupy a smaller volume. This affects Ly-α transit signatures, which are reduced from 20% in the case of no wind interaction to barely any absorption in the extreme stellar wind scenario. Future Ly-α transits could therefore place constraints not only on the evaporation rate of AU Mic b, but also on the mass-loss rate of its host star.

Destination exoplanet: Habitability conditions influenced by stellar winds properties

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Stars interact with their planets through gravitation, radiation, and magnetic fields. While magnetic activity decreases with time reducing associated high-energy phenomena, stellar winds persist throughout the entire stellar evolution. The cumulative effect of stellar winds on exoplanets will dominate over other forms of star-planet interactions. This is crucial for processes such as atmospheric erosion which directly connects with the concept of Habitable Zone planets (HZ) around late-type stars. In order to characterize their influence, we are using one of the most detailed solar models that exist to date (the state-of-the-art Space Weather Modelling Framework) and apply it to the stellar winds domain. In this talk I will summarize the initial results from this investigation, showing how different stellar wind properties are affected by stellar parameters such as the surface magnetic field strength and geometry. These results are used to parametrize the limits for sub-Alfvénic conditions, which drastically affect the type of stellar wind-exoplanet interactions in a given system. Finally, I will discuss the relevance of these results by considering a possible restriction of the classical HZ, which will consider the expected local stellar wind conditions as a function of the surface magnetic field properties of the planet host.

Exoplanet Modulation of Stellar Coronal Radio Emission

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The search for exoplanets in the radio bands has been focused on detecting radio emissions produced by the interaction between magnetized planets and the stellar wind (auroral emission). Here we introduce a new tool to predict the ambient coronal radio emission and its modulations induced by a close-in planet. We explore the radio flux modulations using a limited parameter space of the magnitude of the planetary field, its polarity, the planetary orbital separation, and the strength of the stellar field. We find that the modulations induced by the planet could be significant and observable in the case of hot Jupiter planets above 100 percent modulation with respect to the ambient flux in the 10-100 MHz range in some cases, and 2-10 percent in the frequency bands above 250 MHz for some cases. Thus, our work indicates that radio signature of exoplanets might not be limited to low-frequency radio range. We find that the intensity modulations are sensitive to the planetary magnetic field polarity for short-orbit planets, and to the stellar magnetic field strength for all cases. The new radio tool could provide predictions for the frequency range at which the modulations can be observed by current facilities.

Hot Jupiters accreting onto their parent stars: effects on the stellar activity

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Hot Jupiters (HJs) are massive gaseous planets orbiting close to their host stars. HJs atmospheres are heated by the radiation arising from the star and the heated planetary gas may escape from the planetary gravitational field (Lammer et al. 2003). Several works suggest that some systems show enhanced stellar activity in phase with the planetary rotation period (e.g. Shkolnik et al.2003,2005,2008, Walker et al.2008, Pillitteri et al.2010,2011,2014,2015). In this work, we use a 3D magnetohydrodynamic model that describes a system composed by a star and a HJ and that includes the corresponding planetary and stellar winds, to investigate whether the material evaporating from the planet interacts with the stellar extended corona, and generates observable features. Our preliminary results show that the planetary wind expands and propagates mainly along the planetary orbit. Moreover, part of the planetary wind collides with the stellar wind and a fraction of the planets outflow is funneled by the stellar magnetic field and hits the stellar surface. In both events the material is heated up to temperatures of few MK by a shock that generates X and UV radiation. These phenomena could manifest in the form of enhanced stellar activity in phase with the planet.

A search of planet companions of white dwarfs with XMM-Newton

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We use all avalible XMM-Newton EPIC observations of putative single white dwarfs (WD) to search for sub-stellar companions, in particular, planets. We gathered more than 2 Ms of observations of 116 WD to study their variability in the hard X-rays. We found at least four cases of WD with variable X-ray emission that can be explained by the presence of a Jupiter-like planet.

MHD Effects of the Stellar Wind on Observations of Escaping Exoplanet Atmospheres

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Interaction with the stellar wind and accompanying radiation can result in significant atmospheric erosion, potentially affecting a planet's ability to host life. Previous research indicates the atmospheres of close-in, low-mass planets are highly vulnerable to the effects of XUV driven photoevaporation. However, the effects of the stellar wind on low-mass exoplanet atmospheres have only just begun to be addressed. We present 3D magnetohydrodynamical (MHD) simulations of the effect of the stellar wind on the escaping atmosphere of a magnetized planet in the habitable zone of a low-mass M dwarf. We use the TRAPPIST-1 system as the basis of our simulations and model the planet to have an H-rich evaporating outflow, with a pre-defined mass loss rate. Our results show the atmospheric outflow is dragged and accelerated upon interaction with the stellar wind, resulting in a diverse range of planetary magnetospheres which are strongly dependent on the local stellar wind conditions through the orbit and can vary over timescales as short as an hour. We explore the implications of this wind-outflow interaction on potential observations of escaping atmospheres and show that stellar wind interactions provide an explanation for observed variations in transit absorption features.

INCREASE - A model suite to study the INflucence of Cosmic Rays on Exoplanetary AtmoSpherEs

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The first opportunity to detect indications for life outside of the Solar System may be provided already within this decade. However, the harsh stellar radiation and particle environment of planets in the habitable zone of the favored cool stars could lead to photochemical loss of atmospheric biosignatures. A self-consistent model suite of combined state-of-the-art tools has been developed to study the impact of the radiation and particle environment (cosmic and stellar rays) on atmospheric particle interactions, composition, and climate interactions. This has been employed for an Earth-like N_2-O_2 atmosphere (Herbst et al., 2019) and a feasible planet with an N_2-O_2-CO_2 atmosphere around Proxima Centauri (Scheucher et al., 2020). In a next step, we will extend our model studies to a wide range of possible exoplanetary atmospheres and stellar environments to tackle the following questions: (1) What processes determine whether (rocky) worlds around cooler stars can retain their atmospheres? (2) How do different atmospheres evolve for cool star systems?, and (3) How do results from our study compare with observations? In particular, we will investigate the impact of stellar activity on planetary climate, atmospheric escape, density and composition, surface radiation, the planets radiation dosage, and the impact on potential observables.

Tidal star-planet interaction revealed by its impact on stellar activity

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As the star ages and evolves, its rotation rate decreases and the star spins down. In star-planet systems, the possibility of halting the decrease or even increasing the rotation rate of a star due to tidal interaction exists and an enhanced activity level can trace it. To properly address the tidal interaction, we invoke a reference star that does not host a planet and that has the same age as the planet-hosting star. Therefore, we analyze wide binary and multiple stellar systems that have a planet-hosting star and use its coeval stellar companion as a proxy for the expected magnetic activity level. We have a sample of 37 stellar systems, observed in X-rays with XMM Newton and Chandra, for which we evaluate the component' X-ray luminosity. We expect that the enhanced magnetic activity of the planet host leads to a hotter corona and hence a brighter X-ray source when compared to its stellar companion if the enhancement is due to tidal interaction. With this approach, we will be able to determine if the tidal spin-up process can leave an observable footprint on planet-hosting stars and which star-planet system configuration is prone to significantly changing the activity level of the star.

Planet-induced radio emission from the coronae of M dwarfs

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Star-planet interactions can produce detectable signatures across the electromagnetic spectrum, ranging from radio through to ultraviolet/X-rays. Here I will present a study of the two active planet-hosting M dwarfs Prox Cen and AU Mic, in the context of low-frequency radio emission. Our work is motivated by the exciting new detections of radio emission from low-mass stars, some of which are indicative of star-planet interactions. We model the stellar wind of the two stars, and use our models to assess if planet-induced radio emission could be generated in the coronae of the host stars. The emission mechanism in our model is analogous to the sub-Alfvénic Jupiter-Io interaction. For Prox Cen, we do not find any feasible scenario where the planet can induce radio emission in the stars corona. However, in the case that AU Mic has a mass-loss rate of < 590 times that of the Sun, we find that both planets b/c in the system can induce radio emission from 10 MHz–3 GHz in the corona of the host star, with peak flux densities of 10 mJy. Our predicted emission bears a striking similarity to that recently reported from GJ 1151, which is indicative of being induced by a planet.

The impact of time-dependent stellar activity on the atmospheric chemistry and observability of exoplanets

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Observations of exoplanets used to characterise the chemistry and dynamics of atmospheres have developed considerably throughout the years. Nonetheless, it remains a difficult task to give a full and detailed description using solely observations. With future space missions such as JWST and ARIEL, both expected to be launched within this decade, it becomes even more crucial to be able to fully explain and predict the underlying chemistry and physics involved. In this research we focus on modelling star-planet interactions by using synthetic flare spectra to predict chemical tracers for future missions. We make use of a chemical kinetics code that includes time-dependent stellar spectra and thermal atmospheric escape to simulate the atmospheres of known exoplanets. Using a radiative transfer model we then retrieve emission spectra. This ongoing study is focused on various known planetary systems of which the stellar spectrum has been obtained by the (mega-)MUSCLES collaboration. Preliminary results on these systems show that stellar flares and thermal escape can have a significant effect on the chemistry in atmospheres.

Galactic cosmic ray propagation through M dwarf astrospheres

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Cosmic rays are important in the context of life. Several works have investigated the effects of Galactic cosmic rays at Earths orbit during its lifetime but few works have investigated the effects of cosmic rays around exoplanets. In particular M dwarfs, which have close-in habitable zones, are the perfect candidates for observations of potentially habitable exoplanets. Thus quantifying the flux of cosmic rays reaching exoplanets around M dwarfs is essential. In particular, because cosmic rays can be a source of ionisation and heating of exoplanets atmospheres. Here, we investigate the modulation of Galactic cosmic rays as they travel through the astrosphere of six M dwarfs. GJ436, one of the stars in our sample, has its stellar wind models constrained by X-ray observations. We perform simulations using a combined 1D cosmic ray transport model and 1D MHD stellar wind model. We found that three M dwarfs in our sample have cosmic rays fluxes comparable with Earths around their much closer-in habitable zones. Most of the known exoplanets in our sample have a significantly lower flux of cosmic rays than values observed at the Earth. This includes GJ273b which is the only known planet orbiting the habitable zone of its host star.

A statistical search for Star-Planet Interaction in the UltraViolet using GALEX

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Most of the over 4200 confirmed exoplanets known today orbit very close to their host stars, within 0.5 au. Planets at such small orbital distances can result in significant interactions with their host stars, which can induce increased activity levels in them. In this work, we have searched for statistical evidence for Star-Planet Interactions (SPI) in the ultraviolet (UV) using the largest sample of 1355 GALEX detected host stars with confirmed exoplanets and making use of the improved host star parameters from *Gaia* DR2. From our analysis, we do not find any significant correlation between the UV activity of the host stars and their planetary properties. We further compared the UV properties of planet host stars to that of chromospherically active stars from the RAVE survey. Our results indicate that the enhancement in chromospheric activity of host stars due to star-planet interactions may not be significant enough to reflect in their near and far UV broad band flux.

GJ 436b and the stellar wind interaction: simulations constraints using Lyα and Hα transits

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The GJ 436 planetary system is an extraordinary system. The Neptune-size planet that orbits the M3 dwarf revealed in the Lyα line an extended neutral hydrogen atmosphere. This material fills a comet-like tail that obscures the stellar disc for more than 10 hours after the planetary transit. Here, we carry out a series of 3D radiation hydrodynamic simulations to model the interaction of the stellar wind with the escaping planetary atmosphere. With these models, we seek to reproduce the 56 % absorption found in Ly alpha transits, simultaneously with the lack of absorption in H alpha transit. Varying the stellar wind strength and the EUV stellar luminosity, we search for a set of parameters that best fit the observational data. Based on Ly alpha observations, we found a stellar wind velocity at the position of the planet to be around [250-460] km/s with a temperature of $[3-4]\times 10^5$ K. The stellar and planetary mass loss rates are found to be 2×10^{-15} M$_\odot$ yr^{-1} and $\sim [6-10]\times 10^9$ g/s, respectively, for a stellar EUV luminosity of $[0.8-1.6]\times 10^{27}$ erg/s. For the parameters explored in our simulations, none of our models present any significant absorption in the Hα line in agreement with the observations.

Chapter 5

Extreme Environments of Planets

A new catalog of high-energy irradiation and evaporation of exoplanets

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X-ray observations of star-planet systems are important to grow our understanding of exoplanets; these observation allow for studies of photoevaporation of the exoplanetary atmosphere, and in some cases even estimations of the size of the outer planetary atmosphere. The German-Russian eROSITA mission is performing the first all-sky X-ray survey since the 1990s, and provides X-ray fluxes and spectra of exoplanet host stars over a much larger volume than was accessible before. We have created a catalog of X-ray irradiation levels of several hundred exoplanets, using new eROSITA data as well as archival data from XMM-Newton, Chandra and ROSAT. We estimate mass loss rates of these exoplanets under an energy-limited escape scenario, and identify several exoplanets with strong X-ray irradiation and expected mass-loss that are amenable to follow-up observations at other wavelengths.

First Detection of Exoplanets and Brown Dwarfs Orbiting X-Ray Binaries via Direct Imaging

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X-ray binaries provide fantastic laboratories for understanding the physics of matter under the most extreme conditions. However, there are currently no observational constraints on the AU-size environments of these extreme systems and it remains unclear how the accretion onto the compact objects or the explosions giving rise to the compact objects interact with their immediate surroundings. Here, we present the first high-contrast adaptive optics images of X-ray binaries aiming to probe a variety of phenomena from protoplanetary discs, to debris discs and fallback discs, as well as orbiting planetary companions. These observations target all X-ray binaries within 2 kpc accessible with NIRC2 on KECK. We present key results from this campaign, including the discovery of candidate brown dwarfs and exoplanets orbiting the Gamma-Cassiopeiae analog X-ray binary RX J1744.7-2713. Our talk emphasizes that such observations may indeed provide a major breakthrough in the field, not only for our understanding of the circumbinary environment of X-ray binaries, but also our understanding of how discs and planets can form even in the most extreme environments.

EUV irradiation of exoplanet atmospheres occurs on Gyr time-scales

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In studies of the XUV-driven evaporation of exoplanet atmospheres, it is typically assumed that the time evolution of the unobservable EUV energy band matches that of the more well studied X-rays, and that resulting atmospheric evolution primarily occurs during the saturated phase of the high-energy emission (the first 100 Myr). We investigate EUV time evolution by combining an empirical relation describing stellar X-ray emission with a second relation describing the ratio of solar X-ray to EUV emission. We find that the decline in stellar EUV emission is much slower than in X-rays, and that the total EUV irradiation of planetary atmospheres is dominated by emission after the saturated phase. Our results suggest that models of atmospheric escape that focus only on the saturated phase of high-energy emission are oversimplified, and when considering the evolution of planetary atmospheres it is necessary to follow EUV-driven escape on Gyr time-scales. This could have implications for distinguishing between photoevaporation and core-powered mass-loss as the mechanism that sculpts the observed radius-period valley. We additionally apply these findings to a small sample of planets discovered by the K2 mission in the open cluster Praesepe.

The first high contrast images of near X-ray binaries

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It has been recently argued that X-ray binaries could host planetary systems. However, in high-mass X-ray binaries (HMXB) where the donor star is a massive O-B spectral type star the system is generally orders of magnitude too bright to detect sub-stellar companions. Using the vortex coronagraph from NIRC2, we obtained the first high-contrast images for nine near HMXBs: RX J1744.7-2713, IGR J18483-0311, SAX J1818.6-1703, 1H2202+501, IGR J17544-2619, 4U1700-37, 4U2206+543, RX J2030.5+4751 and Cassiopeiae (Be star). In this poster, we present the first key result of the campaign: evidence of at least one sub-stellar companion in almost all of these extreme systems. A statistical study will also soon be conducted to better understand, among others, the formation of Jupiter-like exoplanets, the frequency of the sub-stellar companions in X-ray binaries, as well as their impact on the system.

The impact of energetic particles on the evolving Earth and young exoplanets

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The present-day Sun is a relatively inactive star. Other stars are much more magnetically active and flare frequently. Young stars have much greater X-ray luminosities than the Sun. Therefore, this suggests that younger stars accelerate energetic particles to higher energies and more frequently than the Sun. These energetic particles could be harmful to any potential life on close-in exoplanets. At the same time, lower energetic particle fluxes could have been important for the beginning of life on Earth, and for exoplanets, by driving the formation of bio-molecules, the building blocks of life.

I will present our recent results that simulate the propagation of stellar energetic particles through the astrosphere of a Sun-like star as a function of its life. These energetic particle fluxes will then propagate through exoplanetary atmospheres, losing their energy by ionising material. Here, I will focus on energetic particle intensities at 1au at particular times in the Sun's past, such as when life is thought to have begun on Earth. Finally, I will also describe how our results can be applied to specific exoplanetary systems, such as HR 2562, which is host to a warm Jupiter.

The Impact of The Supermassive Black Hole and Tidal Disruption Events on Galactic Habitability

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Considering the ever-increasing number of detected exoplanets, a new question arises: are there areas in our Galaxy and epochs with favorable or unfavorable conditions for their habitability? Recent studies are investigating the possible effects of high-energy astrophysical phenomena. We quantify the extent to which the activity of the SMBH at the center of the Milky Way, known as Sgr A*, may have affected the habitability of Earth-like planets in our Galaxy. We focus on the atmospheric loss suffered by planets exposed to X-ray and extreme ultraviolet (XUV) radiation produced during the peak phase of Sgr A*. We find that terrestrial planets could lose an atmospheric mass comparable to that of present day Earth even at large distances (1 kpc). We also investigated the cumulative effects from Tidal Disruption Events (TDEs), which show emission of a burst of high-energy radiation, using the Milky Way as a proxy. The impact from TDEs is found comparable to that of AGN. In particular, planets within distances of 0.1-1 kpc could lose Earth-like atmospheres over the age of the Earth. We conclude by highlighting potential ramifications of AGN and TDEs, and argue that they should be factored into future analyses of inner galactic habitability.

Chapter 6

Star and Planets Formation

Chandra X-ray Analysis of Herbig Ae/Be Stars

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Herbig Ae/Be (HAeBe) stars are intermediate-mass pre-main sequence stars with spectral types B0 to F5, characterized by strong infrared excess and emission lines. X-rays were observed from HAeBe stars but the origin of their emission is unknown. Sun-like stars emit X-rays, due to the interaction of coronal plasma with the magnetic field. This partly explains the X-ray emission in low mass T Tauri stars (TTS), as they possess convective zone. But, HAeBe stars are radiative and not expected to have magnetic field through any dynamo mechanism. Many alternative models, like low mass close companion, star-disk magnetosphere, stellar winds have been proposed but, a convincing explanation for X-ray emission from HAeBe stars has not been determined. In this work, we searched the Chandra data archive with a compiled list of 279 known optical HAeBe stars and found 39 stars emitting in X-rays. Of these 39 stars, 11 are well resolved from their close companion. We use this sample as a test-bed to check for differences in X-ray properties of HAeBe and TTS. The X-ray properties of HAeBe stars such as unabsorbed flux/luminosity, temperature components are correlated with optical/IR properties to understand the mechanism responsible for X-ray emission from HAeBe stars.

The X-ray emission of Intermediate-mass T Tauri stars.

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In Solar-like stars, the interaction of convection with rotation creates an internal dynamo that generates a magnetic field. Pre-main sequence stars up to 3Msun start out with fully convective interiors, but while the low-mass T Tauri stars (TTS) take a long time to develop a radiative core, their higher-mass counterparts, the Herbig Ae/Be stars (HAEBEs), do so rather fast. Therefore, in these stars, the magnetic fields, necessary to heat the corona, are thought to be weak or even absent. Surprisingly, around HAEBEs X-ray emission was detected. Its presence is still a matter of debate: is it from an unknown companion? Or remnant primordial magnetic fields? To solve this problem we study the intermediate-mass T Tauri stars (IMTTS), precursors of HAEBEs. We study the X-ray properties of a sample of IMTTS, and compare them with those of the older HAEBEs and lower-mass TTS. We use archive X-ray observations and our own data recently observed with XMM. We relate X-ray with literature stellar and disc properties, like magnetic fields and accretion rate. We now present preliminary results; the aim is to get a better understanding about the evolution of X-ray emission in young, intermediate-mass PMS.

Stars and planets formation in the starburst cluster Westerlund 1 from the EWOCS project

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Starburst clusters represent an extreme star-forming environment, characterized by intense intracluster ionizing radiation and high stellar density. Starburst clusters are quite rare in the Milky Way today, but they are common in active and interacting galaxies. Their study can thus shed some light on the conditions where stars and planets form in the early Universe. Westerlund 1 is the closest starburst cluster to the Sun (about 4kpc), with a present day total mass ranging between 20000 and 45000 solar masses and a matchless massive stellar population. The cluster also hosts a pulsar, indicating that it already hosted at least one supernova explosion. To select the stellar population of Westerlund 1, both in its core and halo, down to low masses, and study its formation and evolution, and to asses whether stars can form planets in starburst conditions, we set up the Extended Westerlund One Chandra Survey (EWOCS) project, which is based on a 1 Msec Chandra/ACIS-I of the cluster (P.I. Guarcello). I will discuss how the environment can affect the planets formation process, present in details the project, and discuss how we will analyse the evolution of protoplanetary disks in starburst environment.

"Reading between the lines": Probing magnetospheric accretion, winds, and the innermost disk with emission line tomography

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What happens in the innermost disk at the time of planet formation? While direct mapping cannot access these regions, emission (and absorption) lines in young stars trace their winds, accretion-related structures, spots, and innermost disk. In the optical, a large number of species with various excitation potentials can provide information on the temperature, density, and velocity of hot and tiny structures. Using time-resolved spectroscopy covering several rotational and disk orbital periods, we can obtain a very detailed view of the structure and variability of accretion columns and spots and information on the presence and launching points of stellar/disk winds in young stars. In outbursting sources, the temperature variation allows us to spectroscopically access an even larger region of the disk and surroundings. I will present the results on several young stars with different properties, discussing what we can learn from "reading between the (spectral) lines".

Flaring water masers associated with star with exoplanets IRAS 16293-2422

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Water maser monitoring observations of star with exoplanets IRAS 16293-2422 were carried out with the 22-m Simeiz radio telescope from 2020 January to 2021 February. A flare near a velocity spectral feature at +8 km/s was detected. This flare occurred on top of a less powerful, but longer-lasting flare. A correlation is revealed between the exponential growth of the flux density and the decrease in the linewidth, which is characteristic of the behaviour of a maser in an unsaturated state.

Chapter 7

Future Missions

An Arcus View of Stellar Space Weather

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We will propose Arcus, a Medium Explorer (MIDEX) NASA mission, to the upcoming NASA call. One of the three science goals for Arcus is to explore how stars, circumstellar disks, and exoplanet atmospheres form and evolve. The mission provides high-resolution, soft X-ray spectroscopy with effective area EA>250 cm^2 and resolving power R 3000. Two key science topics are to determine the degree of collisional ionization equilibrium during coronal heating, using dielectronic recombination lines, and to study magnetic accretion on young stars using He-like diagnostic line ratios. Both studies will contribute to our understanding of the stars' impact on exoplanet atmospheres.

The Normal-incidence Extreme Ultraviolet Photometer (NExtUP)

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The Normal-incidence Extreme Ultraviolet Photometer (NExtUP) is a smallsat mission concept using innovative, efficient normal-incidence periodic and aperiodic multilayers to form sharp images of stars in 5 EUV bandpasses between 150 and 900 A, down to flux limits two orders of magnitude lower than achieved by the Extreme Ultraviolet Explorer. The primary science goal of NExtUP is to measure the EUV fluxes of stars, a crucial ingredient for understanding the evolution and loss of exoplanetary atmospheres. Employing a prime focus microchannel plate detector, NExtUP is low-cost and efficient, requiring no mechanisms or special orbital conditions. It draws on decades of mission heritage, including similar instruments that observed the Sun. NExtUP would be flown on a MOOG Industries spacecraft, with a mission design developed in collaboration with NASA AMES. We describe the mission concept and its possible enhancement as a high-resolution EUV spectrometer (NExtUS).

Time-Resolved Photometry of the High-Energy Radiation of M Dwarfs with the Star-Planet Activity Research CubeSat

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Know thy star, know thy planet, especially in the ultraviolet. Over the past decade, that motto has grown from mere wish to necessity in the M dwarf regime, given that M dwarf strong and highly variable ultraviolet (UV) radiation are suspected to strongly impact their planets habitability and atmospheric loss. This led to the development of the Star-Planet Activity Research CubeSat (SPARCS), a NASA-funded 6U CubeSat observatory that will be fully devoted to the photometric monitoring of the UV flaring of M dwarfs hosting potentially habitable planets. The SPARCS science imaging system uses a 9-cm telescope that feeds two delta-doped UV-optimized CCDs through a dichroic beam splitter, enabling simultaneous monitoring of a target field in the NUV and the FUV. A dedicated onboard payload processor manages science observations and performs near-real time image processing to sustain an autonomous dynamic exposure control algorithm needed to avoid pixel saturation during flaring events. The mission is currently half-way into its development phase. We will present an overview of the missions science drivers and its expected contribution to our understanding of star-planet interactions, its development status, and the expected performance of the autonomous dynamic exposure control algorithm, a first-of-its-kind onboard a space-based observatory.

SEEJ: SmallSat Exosphere Explorer of Hot Jupiters

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We describe a science mission concept for a SmallSat Exosphere Explorer of hot Jupiters (SEEJ; pronounced "siege"). SEEJ will monitor the X-ray emission of nearby X-ray bright stars with transiting hot Jupiters in order to Monitor the High energy environment of the exoplanets and to measure the lowest density portion of exoplanet atmospheres and the coronae of the exoplanet hosts. SEEJ will use short focal length X-ray Optics and CMOS X-ray detectors to obtain sufficient collecting area with high sensitivity in a low mass, small volume and low-cost package. SEEJ will observe scores of transits occurring on select systems to make detailed measurements of the transit depth and shape which can be compared to out-of-transit behavior of the target system. The depth and duration of the flux change will allow us to characterize the exospheres of multiple hot Jupiters in a single year. The long baselines (covering multiple stellar rotation periods) from the transit data will allow us to characterize the temperature, flux and flare rates of the exoplanet hosts at an unprecedented level. This will provide valuable constraints for models of atmospheric loss.

Name Index