THE ATMOSPHERE OF AN EXOPLANET LOCATED AROUND A G2V STAR

1 Abstract

Studies of the Earth's atmosphere and the surrounding planets of the solar system have been conducted several times. However, the continuation of these studies to exoplanets has come with more technical challenges. We propose to observe an exoplanet located ~1-2AU around a G2V star with Chandra to study the possibility of an atmosphere present and its composition. Using methods similar to previously done studies of the planets is a reasonable course given the comparable situation. Chandra's spatial resolution will ensure that the possible emission lines are not blocked by the host stars activity. The grating spectrometers will allow the identification of specific elements and the sensitivity to soft X-ray emissions will be instrumental in isolating particular signals.

2 Scientific Justification

Previous calculations suggest that the planet has an Earth-like mass, which allows for possibility of its surface gravity being able to retain an atmospheric structure. Depending on the planet's own history, such as volcanic activity and external interactions an atmosphere could have formed (Madhusudhan et al. 2016). The exact composition would depend on these processes but a similar composition to Earth's or even Venus-like is possible. Comparable studies of the solar systems planetary atmospheres have used X-ray emissions to identify elements.

The X-rays detected in the solar system originate from the Sun and their effects vary depending on the presence of an atmosphere. The host star of the exoplanet is of the same spectral classification as the sun, and as such it would be reasonable to assume that the emission processes of the discovered star would be alike those of the Sun. These include stellar X-rays, scattering, fluorescence and stellar wind charge exchange (Bhardwaj et al. 2010; Brightman et al. 2015). The magnetic field of a planet may also have an effect, but that effect is a combination result of the emission from the star and the makeup/magnetic field of the planet.

Stellar X-rays will be created will a variety of energies (soft and hard X-rays). Soft X-rays are produces by the corona, the outer layer of the atmosphere of the star. Soft X-rays have lower energy from 0.1keV to 10keV with longer wavelengths (Bhardwaj et al. 2010). With these lower energies atmospheres of planets will absorb these with ease, and thus the soft X-rays do not penetrate very far into an atmosphere. High temperatures cause the coronas charged particles to undergo thermal Bremsstrahlung radiation (Hickson 2015). Thermal Bremsstrahlung radiation is a process in the presence of hot plasma where electrons are moving in a Maxwell-Boltzmann distribution of velocities. When an electron passes by an ion where the electron is deflected and sped up by the electric or magnetic field, this produces a photon. Higher temperatures will result in more energy and higher velocities. This process will produce a wide continuous spectrum over many photon energies.

Hard X-rays come from stellar flares as well as the star's magnetic activity. The magnetic field lines in a highly ionized gas are forced together, when they connect, they are forced into a newly constructed shape. Magnetic energy is then converted into kinetic and thermal energy which can cause particle acceleration. The particles will follow along the magnetic field lines out into a loop. When they come back to the chromosphere (deeper part of the suns atmosphere) and collide, they undergo the process of non-thermal Bremsstrahlung radiation. Hard X-rays have more energy than soft, landing around 10keV – 100keV. They have very short wavelengths, less than nanometers and this makes them capable of penetrating through many materials, even those of higher density. Thus, these kinds of X-rays can penetrate through a planet's atmosphere perhaps without much interaction of the particles there. However, when interactions occur the high energy levels allow ionization and other related results.

Thomson Scattering is the process where stellar X-rays interact with the free electrons of the atmosphere or magnetosphere of a planet (Bhardwaj et al. 2010; Sobolev 1975). The oscillating electric and magnetic field of X-rays (being a type of electromagnetic radiation) hit the electron which feels the force of the electric field F=qE. The electron itself oscillates in response to the changes in the electric field. The electron then re-emits the energy from the incoming X-rays, the frequency of these is the same as the incoming X-rays. The scattered X-rays often have an electric field that oscillates in a particular direction (polarization).

Fluorescence is a complimentary role to Thomson Scattering. While scattering is an elastic interaction fluorescence is the absorption of the X-ray photon by the atom or molecule, followed by a specific re-emission at a lower energy (Bhardwaj et al. 2010; Bertout 2024; Chamberlain & Sobouti 1962). Energy from the photon causes an electron from the inner most shell to be ejected. An electron in a higher shell will then fall to the lower shell. Because of the energy difference between these shells a photon with a specific energy will be released. By observing the energy of the photon, the element can be identified by this signature.

The stellar wind is a continuous stream of particles ejected from the corona of the sun. The particles include protons and heavier ions and electrons (Bhardwaj et al. 2010; Brightman et al. 2015*)*. The extreme temperatures allow the particles to gain enough velocity to escape a star's gravity. The particles themselves create a plasma that fills the interplanetary space in between bodies while being fast enough that recombination does not happen during flight. The H and He ions are the majority that stay charged until an interaction, such as the collision into the magnetic field or atmosphere of a planet. The stellar wind charge exchange occurs when the charged particles of the stellar wind interact with neutral material or atom. The wind will strip an electron from the material, the electron will then cascade to lower levels as the ion deexcites and emit a UV or (soft) X-ray photon in a non-thermal process (Bhardwaj et al. 2010*)*. Some of the soft X-ray background observed can be because of this effect. The stellar wind can vary rapidly and with change the performance of the SWCX. The emission spectrum of SWCX is narrow emission lines produced by recombination cascades. Aurorae also begin with the SWCX process, when the particles encounter a magnetosphere around a planet the charged particles are trapped. X-ray emission from bremsstrahlung occurs when the charged particles are accelerated in the upper atmosphere. The particles are led to the poles by the magnetic field lines then transfer energy to the gas molecules. After which they are excited and the return to a normal state result in the emission of photons and colors. This is very apparent on the Earth where magnetic field lines funnel the particles to the poles, so there are more interactions there. It should be noted that aurorae can be created through internal magnetosphere processes.

These processes have all been used in previous observations of the solar system and similar cases in more distant observations.

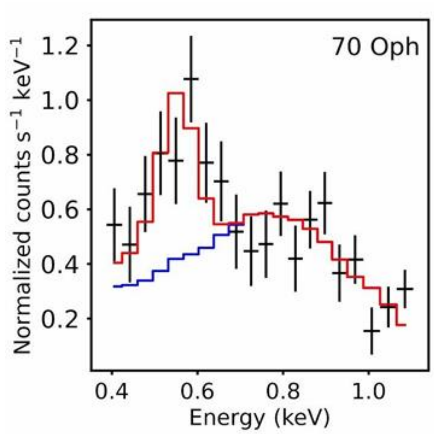

Figure 1: Kislyakova, K.G., Güdel, M., Koutroumpa, D. *et al.* X-ray detection of astrospheres around three main-sequence stars and their mass-loss rates. *Nat Astron* **8**, 596–605 (2024). https://doi.org/10.1038/s41550-024-02222-x [Figure 2, showing the X-ray spectral fingerprints from the astrospheres]. This graph displays the spectral data gathered from XMM-Newton of a sun like star, highlighting certain emission lines, notably the Oxygen lines. Some data is suspected to be from the extended atmosphere of the star, noted in the red of the model. The scattering within the telescope was approximated with the blue line.

Comparisions to previous data could prove useful, however observations of the host star will not be exact despite similar spectral classes. Differences could arise due to age, magnetic and stellar activity, rotations and element abundances. Despite this, the previous data creates an example of possible observation outcomes. The host star of the exoplanet is similarly a sun like star and as such this study sets a precedent for similar observations and data collection.

3 Observations

The following suggested observations will assume that data was retrieved, and the presence of an atmosphere was confirmed. There is a possibility of data from the planet's surface material however the signals would be much weaker than in the presence of an atmosphere and as such would be noticeably different. With the proposed observations using Chandra the following will be done:

(1) Observations of the Host star

Obtaining the high-quality spectrum using Chandra will allow a base level of information for comparisons in the future. Since the star is of the same spectral class as the Sun the results will be more predictable, however still necessary to confirm. The intensity and energy distribution should be recorded as well as any notable stellar activity. Flares and enhanced stellar winds could affect the possible atmosphere and may provide an opening for important observations.

(2) Observations of the exoplanet

Take spectral and imagining data of the region of interest. Repeating this process at separate points in the exoplanets orbit or considering stellar activity may be helpful if no data is retrieved (Brightman et al. 2015; Brightman et al. 2014). The host star's spectrum can be subtracted if spatial separation is not possible. After obtaining the spectrum of the exoplanet further analysis can be conducted.

(3) Basic analysis

The comparison with the host star's spectral data will be the first indication of the presence of an atmosphere. Any different spectral features should be noted and then will be expanded upon with future observations and analysis. These include continuum, broad features and narrow emission lines. It should also be verified that there were no background sources to contaminate the data.

(4) Analyzing the spectrum

Any key features noted should be expanded upon. The scattered spectrum will have the host star's energy distribution, a comparison of lower energies of both spectra can hint towards scattering. The polarization and direction of the X-rays may also be used to confirm its source (Brightman et al. 2014). The intensity has a dependence on the density of free electrons, using Thomson cross section and scattering this can be analyzed to indicate the presence of an atmosphere structure. Thermal broadening may occur due to the velocity of the particles and the temperature may be calculated from such data.

Fluorescent lines will appear at energies lower than the absorbed photons as such a comparison to the original X-ray spectrum and scattering will separate the data. Absorption edges, sudden decreases and narrow emission lines are indicators to specific elements. The database of atomic data for fluorescent lines will be consulted for comparison and identification. The strength of the lines and calculated column density can be analyzed to determine the abundances of elements. Using prior information about the exoplanet may allow for prediction modelling of the potential spectral lines.

The detection of SWCX emission is extra confirmation of an atmosphere and can be analyzed. These lines would be distinct from those of scattering and fluorescence as they come from specific ions. Each line is a stellar wind ion interacting with an atmospheric atom. The intensity of the lines can be used to estimate the density of neutral atoms in the atmosphere and the distribution of emissions will reveal the structure and possible presence of a magnetic field. In combination with other data the atmospheric structure and composition can be understood.

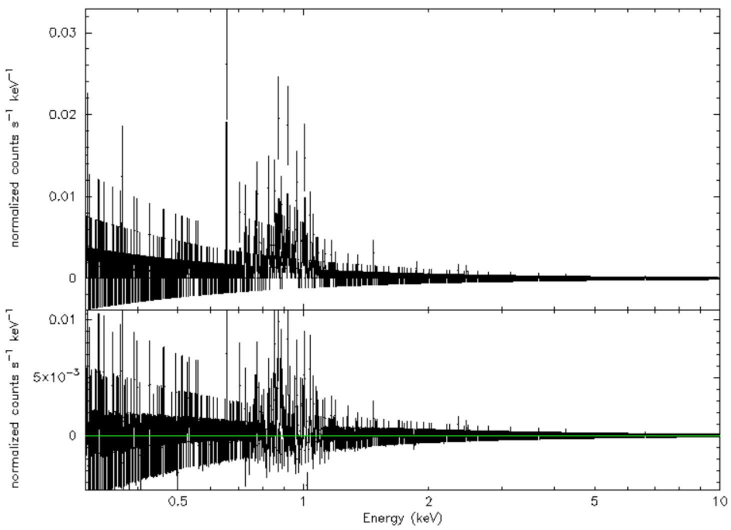

Figure 2: A model of the X-ray emissions of a possible atmosphere of the exoplanet, with a dummy response accounting for the use of an instrument. **Top:** The example X-ray emissions from an atmosphere showing possible spectral features. **Bottom:** The residuals arriving from the dummy response used and thus overprediction of the models' effects.

4 Technical Justification and Feasibility

We request several separate observations to gather comparable data. 75 ks of use of Chandra’s Advanced CCD Imaging Spectrometer (ACIS) for observations of the host star. Using the Low Energy Transmission Grating (LETG) will allow focus on the soft X-rays that create the processes of fluorescence and scattering. A slightly longer observation time allows monitoring of stellar activity. 100 ks of use of the High-Resolution Camera (HRC), ACIS and LETG will provide separated faint signals, spatially resolved imaging and a focus on narrow emission lines for distinguishing processes of the exoplanet. Additional observations of multiple phase orientations may be needed to collect additional data after original data has been analyzed. To identify scattering observations before or after a transit or eclipse could aid in confirmation, 50 ks with HRC as well as the LETG. If stellar activity was observed 50 ks during or following using the LETG will allow for the identification of the elements present in the atmosphere. 75 ks of use of ACIS and the LETG during strong stellar winds will resolve SWCX emission lines.

The example model showcases a possible continuum created from thermal bremsstrahlung and features in the lower part of the spectrum (soft X-rays). These could has arrived because of the SWCX or fluorescence from lighter elements. The model represents an atmosphere structure like that of the Earth’s, and thus actual observations and data might differ. Due to this other model and power laws may be needed in analysis. Using the sensitivity of Chandra, weak emission lines can be detected and thus offer more insight. With similar observations done and the relevant X-ray range (soft) the high spectral and angular resolution become instrumental. It should be noted that the data received from the suggested observations as well as the need for additional observations may vary.

5 Conclusions

The examination of an exoplanet in an environment nearly identical to that of the Earth provides a unique opportunity to study a possible twin of the Earth. It could lead to insight on the development of our planet compared to others similar. The attempt at such observations to confirm the presence of an exoplanet's atmosphere and discover its possible composition will expand the range of study for future exoplanet observations.

6 References

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