Tuning in to star-planet interactions at radio wavelengths
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Summary

Low-mass main-sequence stars like our Sun are continuous sources of outflowing hot magnetised plasma. In the case of the Sun, this is known as the *solar wind*, whereas for other stars they are called *stellar winds.* These types of stars comprise 93% of all stars in our galaxy, and also host the bulk of all exoplanets discovered to date. Therefore, understanding their wind outflows and how they interact with the planets they host is crucial to assessing the long-term evolution of planetary atmospheres, which in turn determines their potential to support life as we know it. The interactions between stellar winds and planets can also produce signals which could be detected with current-generation telescopes.

Current measurements of the winds of low-mass main-sequence stars are limited, and have only been successful in a handful of cases. However, by coupling state-of-the-art magnetohydrodynamic (MHD) models of stellar winds with observational constraints, 3-dimensional snapshots of the wind environments around planet-hosting stars can be obtained. In this thesis, I utilise such models to explore the winds of these stars, and predict the potentially-observable signatures that may arise from their interactions with orbiting planets.

Finding exoplanets with radio telescopes

Analogous of what is observed for the magnetised planets in the solar system, planets orbiting around other stars are expected to exhibit auroral emission at their magnetic poles, particularly at radio wavelengths. Such emission is thought to be generated via the interaction between the planet's own magnetic field and the wind of its host star. If detectable, the emission emanating from the planet's magnetic poles could provide a new window for discovering exoplanets.

The winds of low-mass main sequence stars are predominantly composed of hot magnetised hydrogen, which can strongly absorb the low frequency radio emission that exoplanets are thought to emit at. As a result, if the wind of the host star is very dense, radio emission from the planet may be difficult to detect. Therefore, understanding the stellar wind environment of planet-hosting stars is crucial to determining if radio emission from planets can be detected from Earth.

From our understanding of the auroral emission of the solar system planets, radio emission from exoplanets is expected to be stronger for those with larger radii and smaller orbits. Coincidentally, such planets dominate the current population of known exoplanets. As their presence produces stronger signatures from their host stars, they are more favourable for detection via traditional methods. These planets are known as 'hot Jupiters', which are roughly the size of Jupiter and orbit very close to their host stars.

HD189733b is a well-known hot Jupiter, which orbits its host star at about 3 percent of the distance between the Earth and the Sun. The host star is also very active, and is likely to drive a wind that is much stronger in comparison to the solar wind. As a result, HD189733b has been of particular interest in the context of exoplanetary radio emission. Using a state-of-the-art 3-dimensional magnetohydrodynamics code, in Chapter 2 I simulate the stellar wind of the host star of HD189733b. This model is based on observationally-derived magnetic field maps for the star, which are a key input for these models. I then use the results of the stellar wind model to estimate the frequency and strength of the radio emission for the planet.

The wind of the host star is expected to be quite dense, so it will absorb a large fraction of the radio emission from HD189733b. In Chapter 2, I show that this effect is least pronounced when the planet is near conjunction of the host star, the point in its orbit where it is closest to the observer. The geometry of a planet in conjunction is shown in Figure I. This result illustrates that detection of radio emission from any exoplanet is most favourable when it is near conjunction, which can be used to guide future observations in search of such emission. Outside of conjunction, the exoplanet is said to be 'eclipsed' by the wind of its host star at radio wavelengths, becoming undetectable.

Exoplanets as probes of stellar winds

(i) Radio eclipses of exoplanets

With the concept of radio eclipses of exoplanets established, the next question I asked myself during this thesis was: how do the properties of the stellar wind and geometry of the planetary orbit affect the duration and severity of the eclipse? If we can determine this, we can in theory reverse-engineer observations of exoplanetary radio emission to study the winds of planet-hosting stars.

The 3-dimensional numerical models utilised in Chapter 2 are computationally expensive and time-consuming, and therefore their uses are generally limit to specific cases. As a result, they are not well-suited for parametric studies such as that described above. Simpler models that retain the key physical processes however can be deployed for this. With this in mind, in Chapter 3 I develop a 1-dimensional stellar wind model, which I then couple to another physical model that describes the propagation and absorption of low-frequency radio emission through stellar winds. This model is very fast and flexible, and provides the percentage of exoplanetary radio emission that escapes through the wind of the host star as a function of time, for any set of stellar wind and orbital properties.

Using this model, in Chapter 3 I first illustrate the effects of the stellar wind mass-loss rate and temperature on the duration of the radio eclipse. I find that

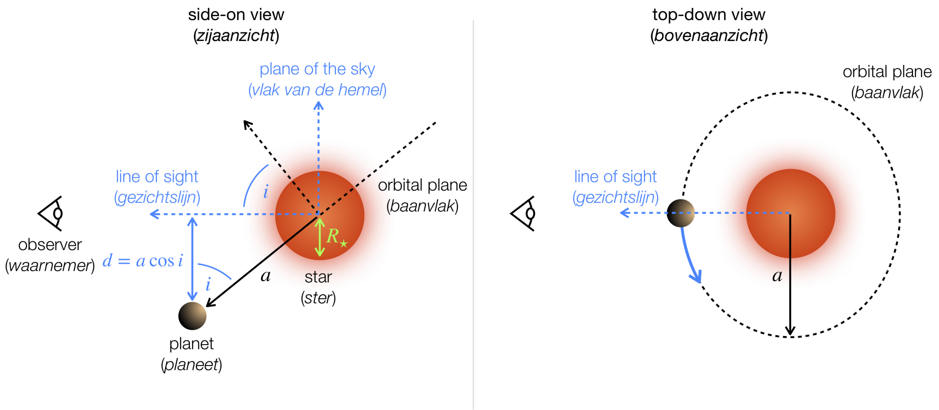

Figure I: *English:* Sketch illustrating the geometry of an exoplanet's orbit around its host star, with an orbital distance a and inclination i. When the planet is closest to the observer, it is said to be in 'conjunction'. In Chapter 2, I show that such a scenario provides the most favourable conditions for detecting exoplanets at radio wavelengths. Note that in the case where d is less than the stellar radius $R_\star$, the planet is said to 'transit' the star (neglecting the size of the planet itself), where it periodically blocks a fraction of the starlight. *Nederlands:* Schets ter illustratie van de geometrie van de baan van een exoplaneet rond zijn moederster, met een baanafstand a en inclinatie i. Wanneer de planeet het dichtst bij de waarnemer is, wordt gezegd dat deze in 'conjunctie' is. In Hoofdstuk 2 laat ik zien dat een dergelijk scenario de gunstigste omstandigheden biedt voor het detecteren van exoplaneten op radiogolflengten. Merk op dat in het geval dat d kleiner is dan de stellaire straal $R_\star$, de planeet de ster 'overgaat' (waarbij de grootte van de planeet zelf verwaarloosd wordt), waar hij periodiek een fractie van het sterlicht blokkeert.

stars with hot, low mass-loss rate winds present more favourable conditions for detecting radio emission from their orbiting planets. In terms of the orbit of the planet itself, transiting exoplanets experience the largest modulation to their radio emission, being most visible during transit of the stellar disk. Additionally, planets orbiting further from their host stars are more easily detected. I then apply the model to the hot Jupiter host τ Boo, showing that the stellar wind properties of planet-hosting stars can be constrained by the morphology of the radio eclipse. Specifically, the duration of time where a specific fraction of the exoplanetary radio emission escapes the system can be directly linked to a combination of stellar wind temperature and mass-loss rate. This provides a potential new method for estimating the properties of the winds of planet-hosting stars, which so far has only been successful in a handful of cases.

(ii) Magnetic star-planet interactions

Exoplanetary radio emission is not the only avenue for studying the winds of low-mass stars, nor is it the only type of radio emission thought to occur due to the presence of planets. Another mechanism that is thought to generate bright radio emission in exoplanetary systems is via the perturbation of the star's own magnetic field due to the motion of the planet, generally referred to as magnetic star-planet interactions (for details see Section 1.5). A key distinction between this and exoplanetary radio emission is that the emission occurs near/on the star itself, as opposed to on the planet. Another thing of note is that the emission is thought to occur at higher frequencies compared to that expected for exoplanets, as these stars can harbour surface magnetic fields that are three orders of magnitude larger than what is seen on the Sun. This is a proposed explanation for the lack of conclusive detections of exoplanetary radio emission, in that it may be generated at a frequency that is too low to penetrate the Earth's atmosphere.

Around all magnetised stars exists a region known as the Alfvén surface, inside which magnetic forces dominate over thermal forces in the solar wind plasma. Inside the Alfvén surface, radio emission can be generated near the star via the perturbation of the star's magnetic field by an orbiting planet. M dwarf stars are of particular interest in this regard, in that they exhibit very strong surface magnetic fields, which are likely to result in large Alfvén surfaces that can enclose a wide range of planetary orbits. Additionally, stars with low stellar wind mass-loss rates tend to have large Alfvén surfaces. For an illustrative sketch, see Figure II.

The two nearby M dwarfs Proxima Centauri (Prox Cen) and AU Microscopii (AU Mic) present potentially suitable conditions for magnetic star-planet interactions to occur. Both stars exhibit strong magnetic fields at their surfaces, and are hosts to multiple confirmed planets. In the case of Prox Cen, recent radio observations may be indicative of that such interactions occurring. In order to assess the viability for magnetic star-planet interactions occurring on these stars, knowing the location of their Alfvén surfaces relative to the planetary orbits is key.

To determine the location of the Alfvén surfaces of Prox Cen and AU Mic, in Chapter 4 I utilise magnetohydrodynamic models similar to those used in Chapter 2 to obtain 3-dimensional snapshots of their stellar wind environments. These

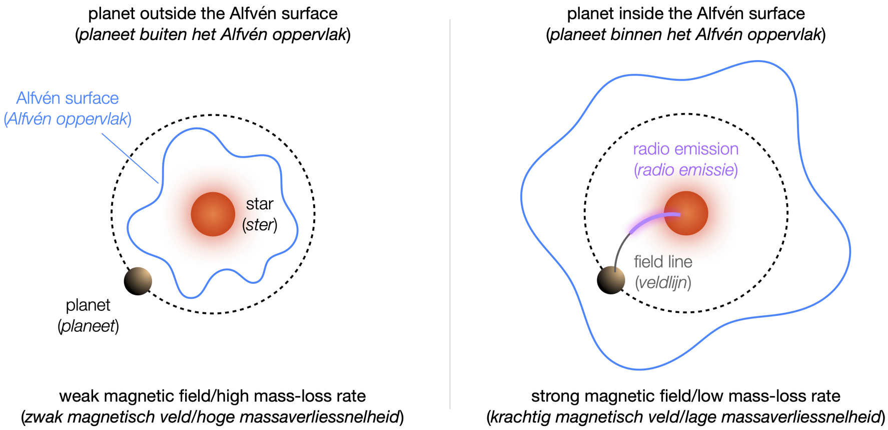

Figure II: *English:* Sketch illustrating the conditions for magnetic star-planet interactions to occur. If the star has a weak magnetic field or a high stellar wind mass-loss rate, planets are unlikely to orbit inside the Alfvén surface (left panel). However, in the case where the host star has a strong magnetic field or low stellar wind mass-loss rate, the Alfvén surface becomes very large, potentially enclosing a wide range of planetary orbits (right panel). When inside the Alfvén surface, the planet can induce the generation of strong radio emission along the magnetic field line that connects it to the star. *Nederlands:* Schets die de voorwaarden illustreert voor het optreden van magnetische ster-planeet-interacties. Als de ster een zwak magnetisch veld heeft of een hoge massaverliessnelheid, is het onwaarschijnlijk dat planeten binnen het Alfvén-oppervlak (linker paneel) draaien. In het geval dat de moederster echter een sterk magnetisch veld heeft of een lage massaverliessnelheid door stellaire wind, wordt het Alfvén-oppervlak erg groot en kan het een breed scala aan planetaire banen insluiten (rechterpaneel). Als de planeet zich binnen het Alfvén-oppervlak bevindt, kan ze sterke radiostraling opwekken langs de magnetische veldlijn die haar met de ster verbindt.

models were constrained using observational data, and the wind properties obtained from them allow for the location of the Alfvén surface to be determined. In the case of Prox Cen, which has an estimated upper-limit for its mass-loss rate, I show that magnetic star-planet interactions are unlikely to occur. For AU Mic however, its mass-loss rate is relatively unconstrained. By varying its mass-loss rate, I illustrate that there is a certain value which places both known planets inside the Alfvén surface. Therefore, if signatures of magnetic star-planet interactions are detected from AU Mic, an upper limit can be placed on its mass-loss rate. This illustrates that the winds of stars can be studied from the detection of magnetic star-planet interactions, complementing the results of Chapter 3.

New methods for identifying potential planet-hosting stars

It is clear that known exoplanetary systems can be studied with using sophisticated magnetohydrodynamic models to assess if different types of star-planet interactions can occur. However, in the case where a signature of such interactions is detected from a star with no known exoplanets, how do we determine if it is of a planetary origin? This is challenging for very active stars. Particularly in the case of smaller planets, the types of signals they induce on the star which are traditionally used to find exoplanets are drowned out by the stellar activity. Therefore, new theoretical models are needed to interpret such signatures, particularly at radio wavelengths.

Recent wide-field radio surveys have begun to detect potential hints of magnetic star-planet interactions from M dwarfs in the Northern sky. So far, none of these stars are confirmed to host any planets. However, WX UMa, a star in the sample of M dwarfs detected at radio wavelengths, has previously had its surface magnetic field mapped. Therefore, a realistic stellar wind environment can be constructed for the star, which in turn allows us to determine the size of its Alfvén surface.

In Chapter 5, I first present a stellar wind model obtained for WX UMa based on its previously-published magnetic field map. I then develop a model that is the first of its kind, which predicts the morphology of the radio emission generated from the star via magnetic interactions with an orbiting planet. Applying the model to WX UMa, I illustrate with this model that its observed emission is best-reproduced by a Neptune-sized planet orbiting the star around every 7 days. While alternative emission mechanisms cannot currently be ruled out for WX UMa, its application exhibits its exciting potential for identifying planet-host candidates from upcoming radio observations.