**Exploring the interactions of M dwarf winds and cosmic rays**
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# English Summary

In this thesis, I have investigated the interaction between M dwarf winds and Galactic cosmic rays and their possible effects on exoplanets' habitability. Fig. 1 shows a schematic that summarises the system studied here. The interstellar medium and stellar wind interaction create a region around the star called the astrosphere. Outside the astrosphere, Galactic cosmic rays diffuse throughout the Galaxy and their intensity is described by the local interstellar spectrum values. To penetrate through the astrosphere, Galactic cosmic rays have to overcome the magnetised stellar wind. Once inside the astrosphere, Galactic cosmic rays can interact with planets orbiting the star. The main parameters to describe this system are the stellar wind properties, the interstellar medium (ISM) properties and the cosmic ray transport description.

M dwarfs, which have close-in habitable zones, are the perfect candidates for observations of potentially habitable exoplanets. However, their winds are tenuous and challenging to observe. In this thesis, I have used numerical simulations to describe the stellar winds of M dwarfs. In particular, I have used a 1D MHD Alfvén-wave-driven wind model in which the stellar wind is heated and accelerated by Alfvén waves induced at the base of the wind. The simulation space parameter is constrained by using observable parameters, such as mass-loss rate, X-ray luminosity, and magnetic field. Observational constraints are not always available and sometimes they are not enough to overcome possible degeneracy in the models. That is the case of GJ 436 stellar wind, discussed in Chapter 2. By using X-ray observations, GJ 436's mass-loss rate was constrained to an upper limit ($\dot{M} < 7.6 \times 10^{-15}\, M_\odot\ \mathrm{yr}^{-1}$). However, this upper limit could be reproduced by different values of stellar magnetic field. This shows how important observational constraints are to describe stellar wind models.

Stellar wind models give us information on the wind properties, such as magnetic field, terminal velocity and mass-loss rate. Combined with ISM properties within each star, the astrosphere distance can be estimated. Chapters 3, 4 and 5 show the diversity of astrospheric sizes found within different M dwarfs, varying from 6 to 6140 au for the sample of stars studied here.

Cosmic rays are important in the context of planetary habitability. Measurements of Galactic cosmic rays reaching Earth have been made for many years. Additionally, cosmic ray transport models to describe the propagation of Galactic cosmic rays to

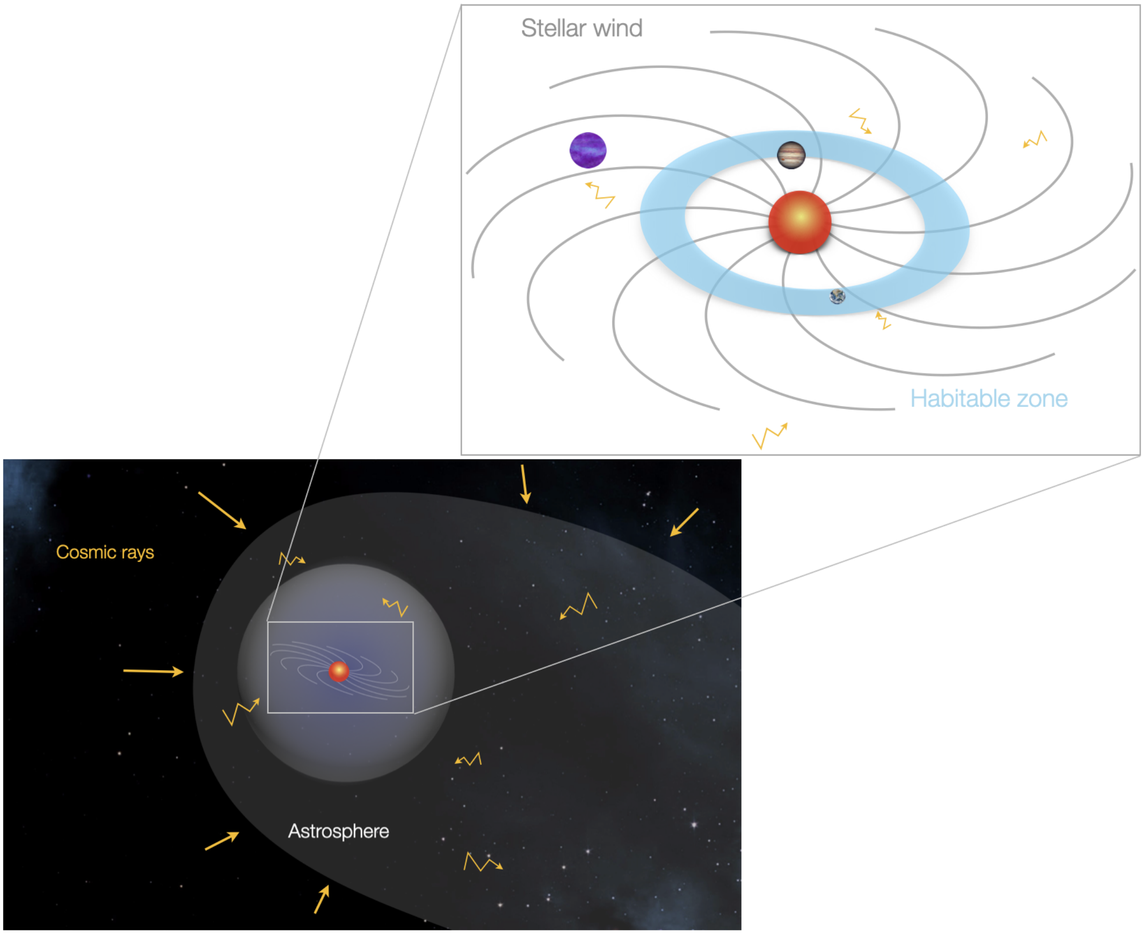


**Figure 1:** Schematic of the stellar system studied in this thesis. The interaction between the ISM and the stellar wind gives rise to an astrosphere. Outside the astrosphere, Galactic cosmic rays diffuse throughout the Galaxy. To penetrate the astrosphere, Galactic cosmic rays need to overcome the magnetised stellar wind. When inside the astrosphere Galactic cosmic rays can interact with the host planets.

Earth have been extensively used to understand the effects of cosmic rays at Earth. However, the effects of cosmic rays around other exoplanets are not well understood. Unfortunately, measurements of cosmic rays on other planets are still not possible. To describe and study the propagation of Galactic cosmic rays through M dwarfs in this thesis, I have used a 1D cosmic ray transport model. These simulations quantify the flux of Galactic cosmic rays reaching any distance in the astrosphere.

The stellar magnetic field and the wind velocity play an essential role in the propagation of Galactic cosmic rays. For instance, a stronger stellar magnetic field result in a larger suppression in the intensity of Galactic cosmic ray (for for fixed turbulence properties, and when compared with a lower magnetic field strength). This can be explained by the fact that a strong magnetic field implies smaller diffusion coefficients. As a consequence, advective processes become more important, resulting in lower Galactic cosmic ray fluxes. Similar, but to a lesser extent, a stronger stellar wind velocity also results in a lower intensity of Galactic cosmic rays in the astrosphere (when compared with a weak stellar wind velocity). This is because a stronger stellar wind velocity implies more advection, which attenuates the flux of Galactic cosmic rays.

The stellar mass-loss rate (or stellar wind density) does not influence the intensity of cosmic rays directly, as the stellar wind density is very low. However, it does affect the size of the astrosphere (through the pressure balance). The Galactic cosmic ray fluxes, however, may be affected by variations in the astrospheric size. If the physical process is dominated by diffusion, the astrospheric size has no effect on the suppression of cosmic rays. This is the case of GJ 436 (see Chapter 3) and GJ 338B (see Chapter 4). On the other hand, if advection is the dominant process, the size of the astrosphere can affect the flux of Galactic cosmic rays. This is the case of AU Mic (see Chapter 5). In summary, advective-dominated systems lead to stronger suppression of cosmic rays, while diffusion-dominated systems lead to little (or no) modulation.

Similar to what happens for Earth, the inclusion of particle drift velocities, due to gradients and curvatures of the stellar magnetic field, also affects the propagation of Galactic cosmic rays through M dwarf astrospheres (see Chapter 5). Overall, for the two stars, in which the particle drift was included, Prox Cen and AU Mic, a larger flux of Galactic cosmic rays was observed (when compared with simulations without the inclusion of particle drift). This can be explained by the fact that both systems had a negative drift velocity at the investigated radial slice, resulting in a larger intensity of cosmic rays. This is due to the fact that particle drift acts simply as an extra advective process in the transport model.

In the sample studied here, with 8 M dwarfs and 12 planets, the majority of exoplanets receive a much lower flux of Galactic cosmic rays than values observed at Earth. The exception, is GJ 15A c, which has a larger semi-major axis and has a flux comparable with the Earth, and GJ 411 c, which also has a larger semi-major axis and receives Galactic cosmic ray fluxes similar to the local interstellar spectrum (LIS). The habitable zone of three stars, GJ 411, GJ 436 and GJ 887 was found to have comparable Galactic cosmic ray fluxes with Earth's values, while the other stars (AU Mic, GJ 15A, GJ273, GJ 338B and Prox Cen) receive a lower flux.

Finally, the results found here may be important to understanding future exoplanet atmosphere observations with JWST and ARIEL. In addition, the exoplanet atmosphere observations will enable us to constrain cosmic ray fluxes in exoplanet atmospheres and possibly help to complete the habitability "puzzle".