EPSC Abstracts
Vol. 6, EPSC-DPS2011-1353, 2011
EPSC-DPS Joint Meeting 2011

Magnetosphere-ionosphere coupling at Jupiter-like exoplanets with internal plasma sources: implications for detectability of auroral radio emissions

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Abstract

In this paper we provide the first consideration of magnetosphere-ionosphere (M-I) coupling at Jupiter-like exoplanets with internal plasma sources such as volcanic moons. We estimate the radio power emitted by such systems under the condition of near-rigid corotation throughout the closed magnetosphere, in order to examine the behaviour of the best candidates for detection with next generation radio telescopes. We thus estimate for different stellar X-ray-UV (XUV) luminosity cases the orbital distances within which the ionospheric Pedersen conductance would be high enough to maintain near-rigid corotation, and we then consider the magnitudes of the large-scale magnetosphere-ionosphere currents flowing within the systems, and the resulting radio powers, at such distances. We also examine the effects of two key system parameters, i.e. the planetary angular velocity and the plasma mass outflow rate from sources internal to the magnetosphere. In all XUV luminosity cases studied, a significant number of parameter combinations within an order of magnitude of the jovian values are capable of producing emissions observable beyond 1 pc, in most cases requiring exoplanets orbiting at distances between ~1 and 50 AU, and for the higher XUV luminosity cases these observable distances can reach beyond ~50 pc for massive, rapidly rotating planets. The implication of these results is that the best candidates for detection of such internally-generated radio emissions are rapidly rotating Jupiter-like exoplanets orbiting stars with high XUV luminosity at orbital distances beyond ~1 AU, and searching for such emissions may offer a new method of detection of more distant-orbiting exoplanets.

1. Introduction

In recent years hundreds of exoplanets have been discovered, many of which have mass greater than or equal to that of Jupiter and orbital semi-major axes of < 0.1 AU, although a significant fraction of planets with Jupiter's mass or greater have been observed with semi-major axes ≥ 1 AU. The possibility of detection of the auroral radio emissions of 'hot Jupiter'-like exoplanets generated by star-planet interactions has been considered by a number of authors, and it has been concluded that such interaction may generate emissions at or above the LOFAR detection threshold [1, 2, 3]. However, despite the importance placed on star-planet interactions, significant components of Jupiter's radio emissions are thought to be generated by the large-scale M-I coupling current system associated with the breakdown of corotation of iogenic plasma in Jupiter's middle magnetosphere. This process generates intense field-aligned electron beams which drive the brightest and most significant of Jupiter's UV auroras and associated radio emissions.

In this paper we consider the application of the model describing Jupiter's M-I coupling current system to Jupiter-like exoplanets with internal plasma sources such as active moons. We begin from the assumption that Jupiter-like exoplanets are strongly illuminated by their parent star, such that the ionospheric Pedersen conductance is high enough to maintain near-rigid corotation throughout the magnetosphere, a condition which maximises the field-aligned current density for a given magnetosphere. We then compute the currents, and thus the resulting radio power output, for varying configurations of Jupiter-like exoplanets. The parameters examined are the plasma mass outflow rate, planetary orbital distance, and rotation rate. We show that, for planets with host stars more active than the Sun, only relatively modest modifications from the jovian system parameters are required to produce potentially-detectable configurations, and by doing so we open up the catalogue of potential candidates for detection by radio telescopes such as LOFAR to a class of planet previously overlooked.

2. Results

Results are shown in Fig. 1 for the four different XUV luminosity cases. The colour indicates the maximum radio power available for each pair of parameter values and the black contours show the maximum observable distances of sources emitting such radio powers, assuming a spectral flux density threshold of 1 mJy. The white contours indicate the orbital distances at which these powers are available, which we note increase with decreasing $\dot{M}$ and, to a lesser extent with increasing Ω_p. This plot shows that the radio power is essentially independent of $\dot{M}$, increases with Ω_J, and increases with stellar XUV luminosity. Thus, for stars with solar XUV luminosity, planets with $(\Omega_p/\Omega_J) \sim 5$ are required to produce radio emissions detectable from beyond ∼10 pc, but this is reduced to e.g. $(\Omega_p/\Omega_J) \simeq 2$ for stars with $(L_{XUV\,\star}/L_{XUV\,\odot}) = 1000$ and $(\dot{M}/\dot{M}_J) \simeq 2$. In all XUV luminosity cases, a significant number of parameter combinations within an order of magnitude of the jovian values are capable of producing emissions observable beyond 1 pc, in most cases requiring exoplanets orbiting at distances between ∼1 and 50 AU. For the two higher XUV luminosity cases, parameter combinations within an order of magnitude of Jupiter's could generate emissions detectable beyond ∼50 pc.

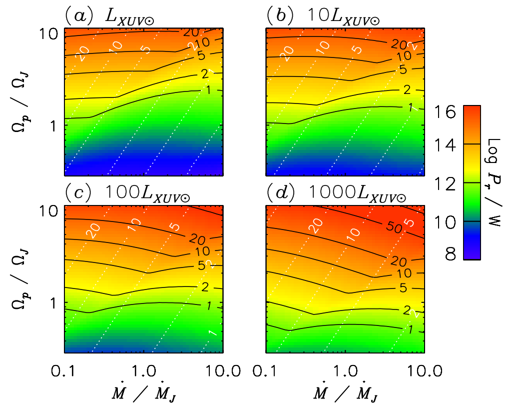

Figure 1: Coloured plots indicating the maximum radio powers P_r available using different pairs of system parameters $\dot{M}$ and Ω_p for, in panels (a)-(d) respectively, the XUV luminosity cases $(L_{XUV\,\star}/L_{XUV\,\odot})$ = 1,10,100, and 1000. Also shown by the black contours are the maximum distances s in pc at which sources of these powers are observable, assuming a detection threshold of 1 mJy, and the white contours show the orbital distances R^*_{orb} in AU at which these maximum powers are available.

3. Summary and Conclusions

The key results of the study can be summarised as follows. The radio power emitted increases with increasing system size, and thus increases with orbital distance within the limit of validity of the high-conductance approximation. The limiting orbital distance, which defines the maximum radio power available for a given set of system parameters, increases with stellar XUV luminosity and planetary rotation rate, and decreases with magnetospheric plasma mass outflow rate. The overall effect is that the radio power emitted increases with planetary rotation rate, but is essentially independent of plasma mass outflow rate since the higher powers available at a given orbital distance for increased plasma mass outflow rate are compensated for by a decrease in the maximum orbital distance to which the high-conductance approximation is valid. In all XUV luminosity cases studied, a significant number of parameter combinations within an order of magnitude of the jovian values are capable of producing emissions observable beyond 1 pc, in most cases requiring exoplanets orbiting at distances between ∼1 and 50 AU. For the higher XUV luminosity cases the observable distances for jovian mass planets can reach ∼20 pc, and massive, rapidly rotating planets could be detectable beyond ∼50 pc.

Acknowledgements

JDN was supported by STFC Grant ST/H002480/1, and wishes to thank S. W. H. Cowley, M. A. Barstow, M. R. Burleigh, G. A. Wynn and an anonymous referee for constructive discussions during this study.

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