THE MAGNETOSPHERES OF EXTRASOLAR GIANT PLANETS

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ABSTRACT

The atmospheres of extrasolar giant planets are subject to high levels of radiation and strong tidal forces from their parent star, and thus represent a unique laboratory to study atmospheric dynamics that is not found within our own solar system. In contrast to previous purely hydrodynamic studies of thermal outflows driven by photoionization heating, we include magnetic and tidal forces for the first time, and we discuss how the modulated wind structure has observational consequences. Our motivation comes from exciting discoveries by NASA’s space-based instruments, most notably those aboard the Hubble Space Telescope (HST). Our work continues to be further motivated by the rapid pace of exciting scientific discoveries (e.g., new exotic planets being uncovered by NASA’s Kepler Mission). The extreme environment of a particular class of extrasolar giant planets with very tight orbits around their host stars (i.e., the “hot Jupiters”) is described, which demonstrates that, along with a new magnetohydrodynamic treatment of dynamics in the upper atmospheres of these planets, allows us to probe an entirely new regime of exoplanet physics.

Introduction

The discovery of gas giant extrasolar planets (EPs) comparable to Jupiter is mass/radius, but heated to high temperatures facilitated by their tight orbits around their host stars (called “hot Jupiters”) has provided a much needed laboratory for testing theories that describe the structure and the dynamics of their atmospheres. These hot Jupiters orbit at distances less than ten stellar radii, or < $1/100^{th}$ of the size of Jupiter’s orbit, where the radiation and stellar wind are $\sim 10^4$ times more intense than at their birth locations [3]. In addition, the existence of an intrinsic planetary magnetic field and stellar wind parameters that are very different from those at the locations of our solar-system planets ([2], [5]) could result in a new type of wind-planet interaction — this also has implications for the survivability of planets.

The expected high temperatures in hot Jupiter atmospheres will therefore lead to an atmospheric scale height which is comparable to a planetary radius, $R_p$, making a “corona” of gas visible via transmission or reflection spectroscopy, as pressure gradients could be driving a wind that could be escaping the planet (see artist conception in Fig.1). This magnitude of the resulting mass-loss translates to timescales for atmospheric evaporation in this extreme environment.

The detection of absorption by hydrogen (H), carbon (C), and oxygen (O) at several planetary radii around the transiting hot Jupiter HD 209458b came as a surprise, since a hydrostatic atmosphere at the expected photospheric temperature $\sim 10^3$ K implies negligible absorption at this altitude [11]. Previous work [10] has argued that a hydrodynamically escaping wind driven by heating from photoionizing (ultraviolet) UV photons (the incoming radiation is powerful enough to separate electrons from the nuclei of atoms) absorbed at lower altitudes can explain the H absorption observed at large projected distances from the planet.

However, recent models (e.g., [8]) have ignored the role of the dynamo-driven planetary magnetic
The expected ionization level of the upper atmosphere implies that electrons and ions are magnetically confined to the planet, while the escape of neutral gas is strongly constrained by drag forces with the confined ions that are collisionally-coupled to the neutrals. While a photoionization-driven outflow may be possible in certain regions, such an outflow would also interact with the magnetized stellar wind. This interaction could manifest itself either through magnetic reconnection (i.e., the release of energy stored in the magnetic field due to sudden changes in its structure) near the planet, driving charged particles into the stellar atmosphere, or in the form of field-aligned current systems, analogous to the type of interaction that has been studied for the Jupiter-Io system [4]. These currents can deposit energy into the stellar atmosphere that can be probed by spaced-based X-ray observations with Chandra.

The ultimate wind velocity structure and density stratification can be impacted by a sufficiently strong magnetic field through geometric effects. The inclusion of stellar tides can act to push the gas down to deeper altitudes, or it can act to accelerate the gas outward, depending on the location relative to the planet-star line. Given the proximity of these hot Jupiters to their host stars, stellar tidal acceleration is no longer negligible.

As a hot Jupiter orbits its parent star, large amounts of magnetic flux are transported from the day to night sides of the planet, which is analogous to the changes seen in the Earth’s magnetosphere during transitions from north to south oriented interplanetary field. This flux transport will lead to significant ionospheric heating from processes such as ion-neutral drag (e.g., [7]). It is therefore critical to understand the role of the magnetic field, not only for its ability to heat the upper atmosphere, but also for its contribution to the escape parameters of the outflow from the planet.

So a few questions we might ask are — when a planetary atmosphere is bombarded with high energy radiation $\sim 10^4$ times stronger than that experienced by any solar-system planet, how does the structure of the atmosphere change? (2) Is “atmospheric escape” possible, and can outflows alter the composition and mass of the planet? For close-in EPs, orbiting at just a few stellar radii, how is the stellar atmosphere affected by the planet-star interaction?

A solid numerical model that captures dominant physics for hot Jupiter atmospheres will lay a solid theoretical foundation crucial for interpreting existing and future data from several NASA observatories: probes of EP upper atmospheres and protostellar outflows through transmission spectroscopy with HST, planet-induced heating of the host-star atmospheres observed by the Chandra X-ray Observatory, and new EPs found by Kepler. In this paper, we provide an overview of the original motivation for these projects in more detail, followed by a summary of our progress. Finally, we conclude with our approach to further develop our models to reach our science goals.

**Method & Results**

To study the mechanisms that drive outflows from the upper atmospheres of hot Jupiters, we have developed several sets of detailed numerical models using the global magnetohydrodynamic (MHD) code ZEUS-MP (described in [1]). Our approach has been to couple analytic descriptions of realistic initial conditions, and post-processing of the results to extract the most important physical quantities for each set of simulations.

This approach has yielded very illuminating results for the upper atmospheres of hot Jupiters. Our combination of semi-analytic descriptions of the thermally-driven wind with the planet’s magnetic field has allowed us to obtain a realistic picture of the magnetosphere for the first time. We have also included the effects of stellar tidal gravity, as for a hot Jupiter, the stellar gravity can dominate throughout a large portion of the magnetosphere.

Fig. 2 shows the steady-state gas density, gas outflow velocity, and field line configuration for...
one of our numerical simulations focused on the vicinity of the planet. We see that in contrast to a spherically-symmetric upper atmosphere that would be predicted by a pure hydrodynamical description, magnetic forces modify the density structure in two very important ways: (1) while gas pressure gradients can successfully drive an outflow in the open field line regions at high magnetic latitudes (i.e., the “wind-zone”), the photoionized gas cannot escape the region of closed field lines at low magnetic latitudes, creating a “dead-zone”, and (2) because the gas in the dead-zone is static, it cannot cool adiabatically by expansion. The temperature therefore remains high and results in a much larger atmospheric scale-height. Using a simple model for photoionization equilibrium our simulations show that this density structure can explain the H absorption observed at high altitudes with HST spectroscopy.

With this basic foundation of models in place, we can now modify our simulation parameters to match those of the best-characterized EPs to quantitatively determine how well our models fit the observations by varying the radius, mass, and orbit of our planet. We have already made more detailed predictions for the extent of the dead-zone for a range of planet masses and radii that span the range of the EPs discovered to date, as well as how the closed field line region size depends upon the ratio of magnetic pressure to gas pressure at the base, the strength of the stellar tide, and a more detailed calculation of the equilibrium neutral H fraction and the temperature-dependent heating and cooling rates [9].

Now that we have shown that a combination of stellar tidal gravity and a magnetic field can support neutral H high up in the planet’s atmosphere, we would like to extend our setup to full 3D simulations that capture the magnetosphere interacting with the surrounding magnetized stellar wind as the planet orbits. Our analysis of currents between the planet and star will help us to determine the physical origin of the X-ray activity observed with Chandra in stars known to host hot Jupiters [6], which is periodic over long timescales and follows the planet around in its orbit. Our models of outflows that include the planetary magnetic field would be quite useful in revealing the detailed physics of the magnetic coupling of hot Jupiters with their parent stars.

A more realistic model includes contributions from various non-ideal MHD effects, which captures additional physics due to finite gas conduc-

Fig. 2.—: An example steady-state configuration for a simulation that includes a thermally-driven wind coupled to an Jupiter-strength intrinsic dynamo planetary magnetic field (blue lines). The axes are shown in units of planetary radii. Continuous color contours show the logarithmic gas density \( \rho \) in units of \( [g \text{ cm}^{-3}] \), and white vectors indicate average fluid velocity magnitude and direction in nearby grid cells. Note the contrast between low density regions at high magnetic latitudes where the wind can escape along open field lines, and the higher density region of static, closed field lines (i.e., the “dead-zone”) where gas is trapped by closed magnetic field lines. The equatorial region contains the bulk of the observable signal in neutral H.

tivity, and the diffusion of positively vs. negatively-charged ions. In particular, we have already implemented the necessary modifications to treat some non-ideal MHD effects in a self-consistent way, which can be applied directly to our problem setups. Non-ideal effects can strongly influence the coupling of gas to the magnetic field as well as the heating and cooling rates in atmospheres, and are therefore necessary for a realistic picture of outflows from highly irradiated EPs to emerge. We defer a detailed treatment of these non-ideal effects to future studies.

**Summary**

We have presented early promising results that
provide a fundamentally new interpretation for transit observations of the hot Jupiter HD 209458b that have discovered H, C, and O at large projected distances from the planet, and we have a more detailed description of the dynamics of the upper atmospheres of hot Jupiters. Our work so far has resulted in a more complete understanding of the environments of close-in EPs, and it has provided a new theoretical framework in which to interpret the HST spectroscopy that probes their upper atmospheres [9].

We can also apply the steady-state density and velocity information to make specific predictions for the fingerprints gases in hot Jupiter atmospheres will make on the observed light coming from these systems, because we can translate our predicted wind/outflow structure into observable characteristics (e.g., line profile measurements including Doppler shifts that depend on the range of gas velocities expected in the magnetically-dominated regions).

With a well-developed set of models in place that has already yielded in promising results, we would like to extend our outflow models to determine how the observed structure of hot Jupiter upper atmospheres can be used to as a tool to probe their magnetospheres and interactions with their host stars already manifested in X-ray observations. Additional physics implemented into our disk outflow simulations would teach us a great deal more about the detailed dynamics of disks, and the quantitative influence of magnetic fields on observable signatures. New NASA observations, such as those taken by the Cosmic Origins Spectrograph that was installed during last HST servicing mission, as well as Kepler and Chandra, will require a clear physical framework in which to interpret results. Our analytic models and accompanying simulations are crucial for for decoding space-based NASA observations of these systems.

REFERENCES