ATMOSPHERIC ESCAPE BY MAGNETICALLY DRIVEN WIND FROM GASEOUS PLANETS

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ABSTRACT
We calculate the mass loss driven by magnetohydrodynamic (MHD) waves from hot Jupiters by using MHD simulations in one-dimensional flux tubes. If a gaseous planet has a magnetic field, MHD waves are excited by turbulence at the surface, dissipate in the upper atmosphere, and drive gas outflows. Our calculation shows that mass-loss rates are comparable to the observed mass-loss rates of hot Jupiters; therefore, it is suggested that gas flow driven by MHD waves can play an important role in the mass loss from gaseous planets. The mass-loss rate varies dramatically with the radius and mass of a planet: a gaseous planet with a small mass but an inflated radius produces a very large mass-loss rate. We also derive an analytical expression for the dependence of mass-loss rate on planet radius and mass that is in good agreement with the numerical calculation. The mass-loss rate also depends on the amplitude of the velocity dispersion at the surface of a planet. Thus, we expect to infer the condition of the surface and the internal structure of a gaseous planet from future observations of mass-loss rate from various exoplanets.

Key words: magnetohydrodynamics (MHD) – planets and satellites: atmospheres – planets and satellites: gaseous planets – planets and satellites: magnetic fields

1. INTRODUCTION

A great number of exoplanets have been found, and many of them are considered to be gaseous giant planets like Jupiter. In particular, some of them orbit very close (<0.1 AU) to central stars, and they are commonly known as hot Jupiters. Transit observations of exoplanets give us not only information about the radius of a planet and its orbital period, but also information of its atmospheric structure and composition by spectroscopic observations. For example, absorption in the H Lyα line and the Na D line is detected at HD 209458b (Charbonneau et al. 2002; Vidal-Madjar et al. 2003). The detection of H Lyα is also confirmed in other planets, such as HD 198733b (Lecavelier des Etangs et al. 2010) and 55 Cnc b (Ehrenreich et al. 2012). The radius of HD 209458b measured in the Na D line is not so different from the apparent radius at other wavelengths, but the radius measured in the H Lyα line is several times larger than the radius of the planet (Vidal-Madjar et al. 2003). The surface temperature of HD 209458b is expected to be approximately 750 K, but the scale height at this temperature is too small to explain the extended upper atmosphere. Therefore, this observation suggests that the temperature of the extended upper atmosphere is much higher than that of the surface (Yelle 2004). Recently, transit observations by an X-ray space telescope show that the apparent radius of the hot Jupiter in the X-ray is a few times larger than the radius of the planet (Poppenhaeger et al. 2013). In addition, transmission spectra during the primary transit and reflectance spectra around the secondary eclipse probe the composition and temperature–pressure structures of the atmosphere of exoplanets (Madhusudhan & Seager 2009, 2010).

Furthermore, transit observations strongly suggest the existence of mass loss from hot Jupiters. The first detection of mass loss from a hot Jupiter is the transit observation of HD 209458b in the UV band (Vidal-Madjar et al. 2003). The high-temperature atmosphere of hydrogen atoms that are escaping from the planet is assumed to make a cometary-tail-like structure; hence, the dimming of a central star by an escaping atmosphere is observed in the UV band, especially in the Lyα line. The mass-loss rate is estimated by the absorption of the Lyα line, and its value reaches at least $10^{10}$ g s$^{-1}$ (Vidal-Madjar et al. 2003). Since this value is model-dependent and not directly observed, the actual value of the mass-loss rate is still uncertain. It is suggested that the mass-loss rate can be either larger by several orders of magnitude (Vidal-Madjar & Lecavelier des Etangs 2004) or lower; for example, gas trapping by a closed magnetic field of the planet leads to a lower mass loss rate (e.g., Yelle 2004).

Observations of the transit by H Lyα showed that the maximum velocity of the escaping gas is as fast as ~100 km s$^{-1}$ (Vidal-Madjar et al. 2003).

It is important to understand the mass loss from a planet because it will strongly affect the evolution of a planet. However, the detailed mechanism of the strong mass loss from exoplanets is still unknown. Various models of the structure of the upper atmosphere and the mechanism of mass loss have been developed. For example, energy-limited escape by X-ray and extreme ultraviolet irradiation from a central star are proposed (Lammer et al. 2003). This is the mechanism by which certain amounts of energy of X-ray and extreme ultraviolet irradiation from the central star heat the upper atmosphere through photodissociation and photoionization, and that drives mass loss from the upper atmosphere. A model that includes X-ray and extreme ultraviolet heating with photochemistry showed the temperature of the upper atmosphere of the irradiated gaseous planets becomes $\gtrsim 10,000$ (K), and the mass-loss rate obtained is $\sim 10^{10}$ g s$^{-1}$ (Yelle 2004, 2006). Also, several models demonstrate that the velocity of the escaping atmosphere can be super-sonic, and hydrodynamic escape dominates over Jeans escape (e.g., Tian et al. 2005; García Muñoz 2007; Murray-Clay et al. 2009). Most of these models that include X-ray and extreme ultraviolet heating suggest the mass-loss rate from hot Jupiters becomes $10^9$–$10^{11}$ g s$^{-1}$, X-ray and extreme ultraviolet (XUV) radiation is strong in the early evolutionary phase of the central star; therefore, hot Jupiters may lose most of their masses by the XUV-driven atmospheric escape in the early phase of a...
system. It is possible for a hot Jupiter to lose its entire envelope and remain only with the solid core, so the atmospheric escape from hot Jupiters may affect the population of the close-in planets (Kurokawa & Nakamoto 2014). Additionally, several previous works suggest that the effects of radiation pressure of the central star on the escaping atmosphere and of charge exchange between the escaping atmosphere and the stellar wind are important to explain the observed spectrum features by using three-dimensional particle simulation (Holmström et al. 2008; Ekenbäck et al. 2010; Bourrier & Lecavelier des Etangs 2013).

Magnetic fields of gaseous planets are thought to also be important for the mass-loss rate and the structure of the atmosphere. Recently, several authors studied the effects of the planetary magnetic fields; for example, magnetically controlled outflows that are launched from planets’ polar regions (Adams 2011) and the upper atmospheres of hot Jupiters modeled with magnetic fields (Trammell et al. 2011, 2014). These authors also discuss the effects on the transit depth and the loss rate of the angular momentum by the planetary magnetic fields (Trammell et al. 2014). The effects of Ohmic dissipation in the atmosphere and the internal structure of hot Jupiters are also studied (Batygin et al. 2014). The effects of Ohmic dissipation in the atmosphere and the internal structure of hot Jupiters are also studied (Batygin et al. 2014). The effects of Ohmic dissipation in the atmosphere and the internal structure of hot Jupiters are also studied (Batygin et al. 2014). The effects of Ohmic dissipation in the atmosphere and the internal structure of hot Jupiters are also studied (Batygin et al. 2014).

However, the effects of the planetary magnetic field and disturbance at the surface of a planet on a mass-loss rate have not been investigated previously. Stellar winds from intermediate- and low-mass stars, like solar wind, are typical examples of a mechanism of mass loss due to the magnetic field. The origin of the energy that accelerates the solar wind is assumed to be the energy of the magnetoconvection and turbulence at the surface. Mass loss by the same driving mechanism as the Sun can occur in exoplanets because they are expected to have their own magnetic fields and strong convection. We calculate the mass loss driven by the magnetic field from gas giants, especially from hot Jupiters, by one-dimensional (1D) magnetohydrodynamic (MHD) simulations and analyze the dependence of the mass-loss rate and the atmospheric structure on various properties of gaseous planets. As a result, the amount of magnetically driven wind can be very large, and it can play an important role in mass loss from gaseous planets.

In Section 2, we represent our calculation method. In Section 3, we describe the calculation result, especially the dependence of the mass-loss rate on the velocity dispersion at the surface of a planet, the radius, and the mass of a planet. Section 4 gives a summary and discussion, in which we derive an analytical expression for the dependence between the mass-loss rate and parameters and compare it with the numerical simulation. We also discuss consistency between the numerical results and the observations.

2. NUMERICAL METHOD

In this paper we extend our numerical simulation code for the solar wind (Suzuki & Inutsuka 2005, 2006) to planetary winds. The simulation code is generally applicable to stars with a surface-convective layer. So far, we have applied it to red giant winds (Suzuki 2007) and young active solar-type stars (Suzuki et al. 2013). Hot Jupiters generally possess a surface-convective layer. Therefore, they are candidates to which our simulation code is directly applicable. Before describing the detailed modeling for the planetary winds, we briefly introduce general properties of stellar winds from stars with surface convection and our simulation code.

In stars with a surface-convective layer, magnetic fields are generated by dynamo action (e.g., Choudhuri et al. 1995; Brun et al. 2004; Hotta et al. 2012), and various types of magnetic waves are excited (Matsumoto & Suzuki 2012, 2014). Among them, Alfvén waves are a promising source which transfers the energy in the surface convection to the upper atmosphere; Alfvén waves, which propagate upward from the surface, heat up the upper corona and drive the stellar wind by various dissipation processes (Goldstein 1978; Heyvaerts & Priest 1983; Terasawa et al. 1986; Kudoh & Shibata 1999; Matthaus et al. 1999).

We time-dependently solve the propagation and dissipation of such MHD waves and consequent heating of the gas in a single open flux tube. In order to take into account closed loops that cover a sizable fraction of the surface, we consider superradially open magnetic flux tubes of which the radial magnetic field strength, $B_r$, is determined by the conservation of magnetic flux,

$$B_r r^2 f(r) = B_{r0} r^2 f_0,$$

where $f(r)$ indicates an areal filling factor of open flux tubes at radial distance $r$, and the subscript “0” represents the surface. We use the same functional form of $f(r)$ as in Suzuki et al. (2013)

$$f(r) = e^{\frac{r-h_l}{h}} + f_0 - \frac{1 - f_0}{e^{\frac{r-h_l}{h}} + 1},$$

where $h_l$ denotes the typical height of closed loops. This is essentially the same form as a superradial expansion factor which was introduced by Kopp & Holzer (1976).

In the 1D open flux tube, we solve the following MHD equations with radiative cooling and thermal conduction,

$$\frac{d\rho}{dt} + \rho \frac{\partial}{\partial r} (r^2 f v_r) = 0,$$

$$\frac{d v_r}{dt} = -\frac{\partial}{\partial r} [\rho v^2 - \frac{1}{28\pi} \frac{\partial}{\partial r} (r^2 f B^2)] + \frac{\rho v^2}{2} \frac{\partial}{\partial r} (r^2 f) - \frac{GM_*}{r^2}.$$

$$\frac{\rho}{4\pi} \frac{d}{dt} \left( r\sqrt{f} v_\perp - \frac{GM_*}{r} \right) = \frac{B_r}{4\pi} \frac{\partial}{\partial r} (r\sqrt{f} B_{\perp}).$$

$$\frac{d}{dt} \left( e + \frac{v^2}{2} + \frac{B^2}{8\pi\rho} \right) + \frac{1}{r^2 f} \frac{\partial}{\partial r} \left[ r^2 f \left\{ \left( \frac{B^2}{8\pi} + \frac{p}{8\pi} \right) v_r - \frac{B^2}{4\pi} \left( B \cdot v \right) \right\} \right] + \frac{1}{r^2 f} \frac{\partial}{\partial r} (r^2 f F_c) + q_R = 0,$$

$$\frac{\partial B_{\perp}}{\partial t} = \frac{1}{r\sqrt{f}} \frac{\partial}{\partial r} \left[ r\sqrt{f} (v_\perp B_r - v_r B_{\perp}) \right].$$

where $\rho$, $v$, $p$, $e$, and $B$ are the density, velocity, pressure, specific energy, and magnetic field strength, respectively, and the subscripts $r$ and $\perp$ denote the radial and perpendicular components; $d/dt$ and $\partial/\partial r$ denote the Lagrangian and Eulerian derivatives, respectively. $G$ and $M_*$ are the gravitational constant and the mass of a central object. $F_c$ is the thermal conductive flux, and $q_R$ is the radiative cooling, which will be explained later. Note that the curvature effects appear as terms instead of $r\sqrt{f}$ terms in the equation of $\partial B_{\perp}/\partial t$. We adopt a two-dimensional Godunov scheme for MHD with the Method of Characteristics for Alfvén waves and Constrained Transport (MOC-CT; Sano et al. 1999). Also, this calculation method for stellar winds from solar-type stars is developed to two-dimensional calculation, and
more detailed aspects of stellar winds have been investigated (Matsumoto & Suzuki 2012).

In the simulations for the solar and stellar winds (Suzuki & Inutsuka 2005, 2006; Suzuki 2007; Suzuki et al. 2013), we set the inner boundary at the photosphere. For the planetary winds in this paper, we set the inner boundary at the position that gives \( p_0 = 10^5 \) dyn cm\(^{-2}\) (= 0.1 bar). We fix the temperature at the inner boundary to the given surface temperature, \( T_0 \). The density at the inner boundary is accordingly determined to give \( p_0 \).

Since the strength and the configuration of the magnetic field in hot Jupiters have large uncertainties, we set up an open magnetic flux tube referring to the observation of the Sun. Recent observations by the HINODE satellite show that the footpoints of open flux tubes in polar regions are anchored to so-called K patches (Tsuneta et al. 2008; Ito et al. 2010; Shiota et al. 2012). The field strength is approximately the equipartition to the gas-internal energy. The magnetic field lines are superradially open with an elevating altitude, and the cross section is typically expanded with a factor of 1000, which indicates that the filling factor of open flux tubes at the photosphere is on the order of 1/1000. As a result, the typical field strengths in the coronal region are on the order of 1 G. Applying these magnetic properties obtained on the Sun to planetary winds, we impose the radial magnetic field so that magnetic pressure is comparable to the gas pressure, or, in other words, plasma \( \beta \)

\[
\beta = \frac{8\pi p}{B^2}, \quad (8)
\]
equals unity at the inner boundary (Cranmer & Saar 2011). In our setups, the value that satisfies this condition is \( B_{r,0} = 1.59 \) kG. The filling factor at the inner boundary is set to be \( f_0 = 1/1600 \), which indicates that the average field strength contributed from open flux tube regions is \( \approx 1 \) G. The filling factor is, in principle, determined by the force balance between the outflowing wind and the magnetic field: larger wind mass flux opens up the closed magnetic structure to lead to larger \( f_0 \). Therefore, we should carefully examine the wind profile obtained in comparison to the field strength in the outer region. In typical cases, the Alfvén point, the location at which the Alfvén velocity equals to the radial flow velocity, is 10–20 planetary radii. This indicates that the kinetic energy of the wind is comparable to the energy of the radial magnetic field at this location. The Alfvén point obtained in units of the object’s radius is quite similar to that for the solar wind, and the adopted \( f_0 \) is assumed to be reasonable.

As the standard case of our simulations, we take a hot Jupiter with the surface temperature, \( T_0 = 1000 \) K. We inject velocity perturbations with amplitude, \( \delta v_0/c_s,0 = 0.2 \), at the inner boundary, where \( c_s \) is the sound speed. Here, we assume a broadband spectrum of \( \delta v_0 \) in proportion to \( 1/v \), where \( v \) is frequency. For the standard case, we adopt the loop height, \( h_l = 0.5 r_0 \), which controls the location where the open flux tube most rapidly opens. When changing the surface temperature, we change \( h_l \) in proportion to \( T_0 \), because we expect that \( h_l \) is scaled by the pressure-scale height, which is \( \propto T_0 \).

We perform simulations of hot Jupiters with the solar metallicity and take the radiative cooling (Equation (6)) from the solar abundance gas. In the simulations for the solar and stellar winds (Suzuki & Inutsuka 2005, 2006; Suzuki 2007; Suzuki et al. 2013), we have taken the optically thin radiative cooling for the coronal plasma (Landini & Monsignori-Fossi 1990; Sutherland & Dopita 1993) and empirical radiative cooling for the chromospheric gas that takes into account optically thick effects based on observations of the solar chromosphere (Anderson & Athay 1989a). For the simulations of hot Jupiters, we need to prescribe the radiative cooling for gas with lower temperature down to \( \approx 1000 \) K. In this paper, we adopt a simple treatment by extending the empirical cooling rate (Anderson & Athay 1989a), which is proportional to density, \( 4.5 \times 10^3 \rho \) (erg cm\(^{-3}\)s\(^{-1}\)). We switch off the cooling when the temperature becomes lower than the surface temperature, \( T_0 \). This treatment is probably too simplified; we plan to elaborate upon the treatment of the cooling in our future works (see Section 4.3).

As shown in Equations (3)–(7), our treatment is based on one fluid MHD, which requires good coupling between gas and magnetic fields. To fulfill this condition, sufficient electrons are necessary to couple field lines and weakly ionized media, although the required ionization degree can be as small as \( 10^{-10}–10^{-5} \), whereas the actual value depends on density.

In our calculation we assume the ideal MHD approximation. However, it is not clear whether or not the ideal MHD approximation is applicable for the calculation of hot Jupiters, because the temperature is not so high, \( \approx 1000 \) K, and the ionization degree is assumed to be small. Here we show the applicability of the ideal MHD approximation for our calculations of the atmosphere of hot Jupiters following an estimate for the atmosphere of brown dwarfs by Sorahana et al. (2014). An induction equation is expressed as follows:

\[
\frac{\partial B}{\partial t} = \nabla \times (v \times B) - \eta (\nabla \times B), \quad (9)
\]

where \( \eta \) is resistivity. This equation describes the evolution of the magnetic field, and \( \eta = 0 \) corresponds to the ideal MHD approximation. If the second term of the right-hand side dominates over the first term, the magnetic field diffuses out, and the ideal MHD approximation is no longer valid. The most dominant origin of the resistivity in the atmosphere of hot Jupiters is the collision between electrons and neutral particles. This resistivity depends on temperature and an ionization degree, and it can be expressed as

\[
\eta \approx 200 \frac{\sqrt{T(K)}}{x_e} \left( \text{cm}^2 \text{s}^{-1} \right) \quad (10)
\]

(e.g., Blaes & Balbus 1994). To estimate the applicability of the ideal MHD approximation, it is useful to introduce a magnetic Reynolds number,

\[
R_m = \frac{v L}{\eta}. \quad (11)
\]

\( L \) is a typical length of a system. If the magnetic Reynolds number \( R_m \) is quite a bit larger than unity, the ideal MHD approximation is applicable. For the typical length of the system, we use the typical wavelength of the Alfvén wave that we are injecting as a perturbation,

\[
L \sim v_A \tau \sim c_s \tau, \quad (12)
\]

where \( v_A \) is the Alfvén velocity and almost the same as \( c_s \), because we assume the equipartition of gas pressure and magnetic pressure for the magnetic flux tube in our calculation. \( \tau \) is a typical timescale and is given approximately by the pressure-scale height of the atmosphere divided by the sound speed of the surface. In the situation in which a planet has a Jupiter radius and Jupiter mass and the surface temperature is 1000 K, the typical timescale can be written as

\[
L \sim 270 \text{ km} \left( \frac{c_s}{2.6 \text{ km s}^{-1}} \right) \left( \frac{\tau}{100 \text{ s}} \right)^{-\frac{1}{2}} \quad (13)
\]
from Equation (12). From Equations (10) and (13), the estimation of \( R_m \) is as follows:

\[
R_m = 2.2 \left( \frac{v}{0.5 \text{ km s}^{-1}} \right) \left( \frac{\tau}{100 \text{ s}} \right) \left( \frac{\tau}{10^{-8}} \right),
\]

where \( v \) is normalized by the value of the velocity dispersion we are injecting, \( \delta v = 0.2c_s \). According to Equation (14), the ideal MHD approximation is applicable to the description of the atmosphere of hot Jupiters even if the ionization degree is not so large. The requirement condition for the ideal MHD approximation is more mild in the upper atmosphere, because the amplitude of Alfvén waves becomes larger because the density of the atmosphere decreases. \( \tau, L \), and many other terms can vary with different conditions, because hot Jupiters have a variety of properties. For example, the scale height is significantly large in a gaseous planet with a smaller mass, larger radius, and, hence, lower surface gravity. In this case, the typical timescale \( \tau \) is larger because of its large-scale height; therefore, the ideal MHD approximation is also better.

### 3. RESULTS

In this section we describe the parameter dependence of the mass-loss rate from gaseous planets and the atmospheric structure.

#### 3.1. Dependence on Velocity Dispersion

First, we show the relation between the velocity dispersion of the magnetic field at the surface of planets and the mass-loss rate from gaseous planets as well as the atmospheric structure. Perturbations at the surface excite MHD waves, and they propagate upward. MHD waves dissipate in the upper atmosphere, then gas is heated and given momentum. Here we assume that the Poynting flux of the MHD waves driven by disturbance at the surface drives gas flow from gaseous planets. In this calculation, the disturbance of the magnetic field is given at the photosphere of gaseous planets. The total energy transported by MHD waves varies with the given strength of the disturbance; therefore, the mass-loss rate should depend on the velocity dispersion. The origin of the disturbance is turbulence that is caused by convection. For example, the velocity dispersion of turbulence at the photosphere of the Sun is about 20%–30% of the sound speed (Matsumoto & Kitai 2010). The strength of turbulence at the surface of exoplanets is unknown, so we treat the value of the velocity dispersion as a parameter. We adopt its value comparable to or less than the value at the Sun. In the case of young gaseous planets, the velocity dispersion of turbulence might be very large because cooling due to convective heat transport is expected to be active. Therefore, the values of the parameters we adopted for this calculation and the resultant mass-loss rate might be underestimated.

The relation between the velocity dispersion at the surface of gaseous planets and the mass-loss rate is shown in Figure 1. Mass-loss rate increases with an increase of the value of the velocity dispersion because of the larger energy deposition in the magnetic flux tube. In the low-velocity dispersion region the mass-loss rate increases very rapidly with \( \delta v \), but in the high-velocity dispersion region the mass-loss rate increases very slowly. In spite of the increase of energy deposited to the magnetic flux tube, the mass-loss rate saturates. This result suggests that there is an upper limit of the mass-loss rate that is driven by magnetic energy. The mass-loss rate increases mainly due to the increase of the density in the wind, which also enhances the radiative cooling because it is in proportion to \( \rho^2 \) in the optically thin limit. As a result, a larger fraction of the input Poynting flux is lost by radiation rather than transferred to the kinetic energy of the wind (Suzuki et al. 2013). This is the main reason why the mass-loss rate saturates for the large \( \delta v \) limit.

The structures of temperature, density, and radial velocity of the atmosphere are shown in Figure 2. Temperature at the near-surface region is approximately constant, and its value is the same as the surface temperature, 1000 K, while gas is heated, and the temperature increases rapidly to over 10,000 K in the upper atmosphere. Corona-like regions appear in the upper atmosphere of the gaseous planets, whereas the temperature here is much lower than the temperature of the solar corona (\( \sim 10^6 \) K). The density profiles of the lower atmosphere are almost the same regardless of the given values of the velocity dispersion, but they change in the regions where the temperature rises rapidly due to the dissipation of MHD waves. If the value of the velocity dispersion is larger, a larger amount of gas is uplifted, and the density decreases more gradually than in the case with the smaller velocity dispersion.

The value of the velocity dispersion and the strength of convection at the surface of exoplanets are unknown. The origin of the velocity dispersion at the surface of the Sun is considered to be turbulence in the surface-convective layer. While a similar mechanism is assumed to operate in gaseous planets, in hot Jupiters the radiative–convective boundary is in a deep location (\( \gtrsim 1 \text{ kbar} \); Burrows et al. 2003; Fortney et al. 2007). However, convective overshoot and propagating waves from the convection region may provide the injected \( \delta v \) in our paper, whereas \( \delta v/c_s \) might be smaller than the typical solar value because of the deeper radiative–convective boundary. On the other hand, we cannot imagine that there is no flow on the surface of the rotating gaseous object irradiated from one side. Indeed, recent numerical studies for atmospheric circulation on hot Jupiters suggest that equatorial wind speeds can reach 2–5 km s\(^{-1}\) (Showman & Guillot 2002; Cooper & Showman 2005; Dobbs-Dixon & Lin 2008). These results imply that supersonic atmospheric flow can exist on the surface of hot Jupiters; therefore, turbulence may be created in the atmosphere of hot Jupiters. In the following section, we adopt \( \delta v = 0.2c_s \) as a typical value of the velocity dispersion at the surface of gaseous planets.
3.2. Dependence on Planet Radius

Next we describe the relation between the radius of gaseous planets and the mass-loss rate. The observed value of the radius of a hot Jupiter varies from 0.8\(R_J\) to 2\(R_J\). We calculate the dependence of the mass-loss rate and the atmospheric structure on the radius of the planet. Here we adopt 1000 K for the surface temperature and Jupiter’s mass for the mass of the planet.

The change of the mass-loss rate with the radius of a planet is shown in Figure 3. The mass-loss rate is small when the radius of a planet is small, but it increases dramatically as the radius of a planet increases. As shown in Figure 3, the mass-loss rate increases by an order of magnitude when the radius is doubled. Therefore, hot Jupiters with inflated radii are expected to have a larger mass-loss rate compared with that of ordinary hot Jupiters, if the values of the surface temperature, mass of the planets, and the velocity dispersion at the surface are similar.

Figure 4 shows the relations between the atmospheric structures and the radius of the planet. The temperatures of the upper atmospheres are heated up to \(\sim 10^4\) K in all cases, but heating starts at a lower altitude in the case in which the radius is smaller. The speeds of the planetary winds are not so different in all cases, but are slightly faster in planets with smaller radii because of the difference of the escape velocities that is determined by surface gravity. We give a detailed description of the dependence between the radius of a planet and the mass-loss rate in Section 4.1.

3.3. Dependence on Planet Mass

Here we describe the relation between the mass of a planet and the mass-loss rate. To date, many exoplanets with varied mass have been detected from rocky planets ranging from those with Earth-size masses to gas giant planets with super-Jupiter masses. Here we change the masses of planets from 0.3\(M_J\) to
1.5 \, M_J$ and calculate the mass-loss rate and the atmospheric structure. The surface temperature is set to 1000 K, and the radii of planets are set to Jupiter’s radius.

The relation between planet mass and the mass-loss rate is shown in Figure 5. As the mass of a planet increases, gas flow from the planet decreases, which is understandable. The structures of the temperature, density profile, and radial velocity profile are shown in Figure 6.

As shown in the bottom panel of Figure 6, the acceleration of planetary winds depends on planet mass. The speed of the planetary wind from the 0.3 $M_J$ planet is particularly small because the wind velocity is roughly scaled by the escape velocity $\sqrt{M_p/R_p}$. However, the mass-loss rate from the planet is very large in spite of its slow wind, because the density of the planetary wind is very large, as shown in the middle panel of Figure 6. Slow and dense planetary wind blows out from a lighter planet, and fast and low-density wind blows out from a heavier planet.

3.4. Dependence on Radius and Mass

We previously described the result of a calculation that changed only one parameter. Here we show the dependence of the mass-loss rate on both the radius and mass of a planet. From the previous discussion, the mass-loss rate increases with an increase in the radius of a planet and decreases as the mass of a planet decreases. Both axes in Figure 7 are logarithmic scale. Each line corresponds to the mass of the planets, and they are approximately parallel.

4. SUMMARY AND DISCUSSION

4.1. Parameter Dependence of Mass Loss Rate

Here we discuss the dependence of the mass-loss rate from gaseous planets on planet radius and mass. We assume that the surface temperatures of the planets are 1000 K, and the value of the velocity dispersion at the surface is constant, 20% of the
Figure 6. Mass dependence on the atmospheric structure. (a) Temperature structure, (b) density profile, and (c) radial velocity profile. The horizontal and vertical axes are the same as in Figure 2. The dotted, dashed, solid, and dot-dashed lines correspond to the cases with $M_p = 0.3\, M_J$, $0.7\, M_J$, $1.0\, M_J$, and $1.5\, M_J$, respectively.

Figure 7. Relation between the radius of a planet and the mass of a planet and the mass loss rate. The horizontal axis is the radius of planets normalized by Jupiter’s radius, and the vertical axis is the mass-loss rate. Note that both axes are logarithmic scale. The dotted, dashed, solid, and dot-dashed lines correspond to the mass of $0.3\, M_J$, $0.7\, M_J$, $1.0\, M_J$, and $1.5\, M_J$, respectively.

The sound speed for simplification. As described in Section 3, the mass-loss rate from gaseous planets increases with radius and decreases with mass. This can be understood by the dependence of the scale height of the atmosphere on the surface gravity as follows. In our model, MHD waves caused by a disturbance of the atmosphere at the surface of the planet propagate into the upper atmosphere, and the planetary wind is driven by the dissipation of the energy of the MHD waves. As shown in Figures 2, 4, and 6, the region where the atmosphere is heated and accelerated rapidly is located a small percentage of the planetary radius above the surface of the planet. The mass-loss rate from the planet depends on the density of the region where the planetary wind is accelerated, and its density varies with the scale height of the atmosphere. The mass-loss rate should increase with the scale height of the atmosphere, because the density of the upper atmosphere with large-scale height is large. The mass-loss rate and other parameters are expected to be related by the following equation

$$\frac{1}{2} M v_{esc}^2 \propto 4\pi R^2 \rho(r_c) v_w \langle \delta v^2 \rangle, \tag{15}$$

where $v_{esc}$, $v_w$, and $\delta v$ correspond to the escape velocity at the surface of an object, Alfvén velocity, and velocity dispersion, respectively. The right-hand side is the energy flux at the transonic point where the wind velocity coincides with the sound velocity $r_c$ of the planetary wind, and the left-hand side is the kinetic energy transported by the planetary wind per unit time. Planetary wind is assumed to stream out from open flux regions which probably cover a fraction of the surface. In addition, only a small fraction of the injected energy from the surface is transferred to the final kinetic energy of the wind after suffering from the reflection of wave and radiative energy loss. 
(e.g., Suzuki et al. 2013). By expressing these corrections as $f_c$, Equation (15) can be written as follows:

$$\frac{1}{2} \dot{M} \delta v^2 = f_c \cdot 4\pi R^2 \rho(r_c) v_w \delta v^2.$$  \hspace{1cm} (16)

Escape velocity is

$$v_{esc}^2 = \frac{2GM}{R}.$$ \hspace{1cm} (17)

The value in the Sun is $f_c \sim 10^{-5}$, and the value of $f_c$ is expected to be in the range $10^{-3} - 10^{-6}$ (Suzuki et al. 2013). By using these corrections, we can express the mass-loss rate as the following equation

$$\dot{M} = f_c \cdot 4\pi R^2 \rho(r_c) v_w \delta v^2.$$ \hspace{1cm} (16)

From the results of our calculations, values of $f_c$ in hot Jupiters vary from $\sim 10^{-3} - 10^{-6}$ depending on the parameters. A typical value is a few times $10^{-6}$, for example, $f_c \simeq 3.21 \times 10^{-6}$ in the case that $R = R_J$, $M = M_J$, the surface temperature is 1000 K, and the velocity dispersion at the surface is 0.2$c_c$.

To estimate the mass-loss rate from gaseous planets, we have to estimate the density profile of the atmosphere because the density at the transonic point controls the mass-loss rate. First, we assume that the atmosphere is in hydrostatic equilibrium. Although the region where the planetary wind is accelerated by the dissipation of MHD wave energy is no longer in hydrostatic equilibrium, the hydrostatic density structure is still a reasonable approximation in the subsonic region. The density profile of the atmosphere in hydrostatic equilibrium determines the density in the acceleration point, and it influences the mass-loss rate. The equation of hydrostatic equilibrium is written as

$$\frac{1}{\rho} \frac{d \rho}{d r} + \frac{GM_p}{r^2} = 0,$$ \hspace{1cm} (18)

where $\rho$ is the pressure of the atmosphere, $\rho$ is the density, and $M_p$ is the mass of a planet. By assuming isothermal flow, the density profile is derived as

$$\frac{\rho}{\rho_0} = \exp\left( - \frac{GM_p}{c_s^2} \left( \frac{1}{R} - \frac{1}{r} \right) \right) = \exp\left( - \frac{r - R}{H_0} \frac{R}{r} \right).$$ \hspace{1cm} (19)

by using the scale height $H_0 = N_A k_B T / \mu g_0$. $\rho_0$ is the density at the surface. This is an approximate expression for the density profile of the atmosphere. By using these equations, we can obtain an expression for the mass loss rate,

$$\dot{M} \propto \frac{R^3}{M} \exp\left( \frac{G r_c - R M}{c_s^2 r_c R} \right).$$ \hspace{1cm} (20)

The acceleration point of the planetary wind $r_c$ is about twice as large as the planetary radius, and $(r_c - R) / r_c$ is on the order of unity. We fit the factors assuming $(G/c_s^2) (r_c - R) / r_c$ is constant for simplification. As a result, the dependence of the mass-loss rate on a radius with the same mass can be expressed as the following equation

$$\dot{M} = 1.109 \times 10^{-14} \left( \frac{R}{R_J} \right)^3 \exp\left( -3.27391 \frac{R_J}{R} \right) \text{g s}^{-1}. \hspace{1cm} (21)$$

This analytically derived parametric dependence of the mass-loss rate is shown in Figure 8. Good agreement with our numerical simulation can be seen in the figure.

### 4.2. Comparison with Observation

Although observations of the mass-loss rate from hot Jupiters are limited, a lower limit of the mass-loss rate is estimated from the light curve during transit. According to observation and analysis, it is estimated that the lower limit of the mass-loss rate from HD 209458b, which is considered a typical hot Jupiter, is $10^{10}$ g s$^{-1}$ (Vidal-Madjar et al. 2003). Another transit observation also suggests that the mass-loss rate from HD 209458b is in the range $(8-40) \times 10^{10}$ g s$^{-1}$ (Linsky et al. 2010). Note that these values of the mass-loss rate are model-dependent; therefore, they are not directly observed values. In our calculation, the values of the mass-loss rate are $1.8 \times 10^9$ g s$^{-1}$, $2.4 \times 10^{10}$ g s$^{-1}$, and $1.2 \times 10^{12}$ g s$^{-1}$, respectively; their values are comparable with the estimation of the lower limit of the observation. The mass-loss rate in the case of $\delta v = 0.2c_c$, is the value most similar to the estimated value and previous work. Additionally, a velocity component as fast as $\sim 100$ km s$^{-1}$ has been observed (Vidal-Madjar et al. 2003). Our calculations show that the velocity of the escaping atmosphere is supersonic in all cases, and the values exceed 100 km s$^{-1}$ in some cases. These results are consistent with observations. The mass-loss rate depends on the velocity dispersion, surface temperature, radius, and mass of a planet, but these quantities can be determined by observations in the near future, except for the velocity dispersion. In other words, we can estimate the amplitude of the velocity dispersion at the surface of gaseous planets if our mechanism explains the observed mass-loss rate from gaseous planets.

### 4.3. Future Work

In this paper, we calculate the mass-loss rate from hot Jupiters and discuss its dependence on the velocity dispersion at the surface, radius, and mass of a planet with constant surface temperature. The adopted surface temperature of a planet is 1000 K, which is considered to be a typical temperature of hot Jupiters. To calculate the mass-loss rate from lower-temperature planets by decreasing the surface temperature, we should refine our calculation with more detailed thermal physics. We can then discuss the dependence of the mass-loss rate on the surface temperature in the near future. The surface temperature of a
planet strongly depends on irradiation from the central star, especially in a region near the star; therefore, the surface temperature should be correlated with the semimajor axis of the planet. Calculating the mass-loss rate not only from a hot Jupiter, but also from a gaseous planet located at several astronomical units from a central star is the focus of our next work.

The present treatment of the radiative cooling, particularly for gas with $T < 10^4$ K, is crude. As described in Section 2, we adopt the empirical radiative loss function for the solar chromosphere (Anderson & Athay 1989a) for gas with $4000 \text{ K} \lesssim T \lesssim 10^4$ K, in which the main coolants are H ii, Mg ii, Ca ii, and Fe ii (Vernazza et al. 1981). The cooling rates for these species are smaller for gas with lower temperature (Anderson & Athay 1989b). On the other hand, molecules (e.g., CO, SiO, CS, OH, H2O) supersede them as dominant coolants (Tsuji 1967, 1973). Although the cooling rate of these molecules seems roughly comparable to that of the main coolants for the solar chromosphere (e.g., Muchmore et al. 1987, for SiO), the precise cooling rate depends on the actual structure of an atmosphere (Muchmore et al. 1987). At present, we cannot tell whether our simplified treatment for the cooling overestimates or underestimates the radiative loss; in a future study, we need to incorporate these species with radiative transfer in a self-consistent manner into our dynamical simulations.

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REFERENCES

Adams, F. C. 2011, ApJ, 730, 27
Anderson, L. S., & Athay, R. G. 1989a, ApJ, 336, 1089
Anderson, L. S., & Athay, R. G. 1989b, ApJ, 346, 1010
Batygin, K., & Stevenson, D. J. 2010, ApJL, 714, L238
Batygin, K., Stevenson, D. J., & Bodenheimer, P. H. 2011, ApJ, 738, 1
Blanc, O. M., & Balbus, S. A. 1994, ApJ, 421, 163
Bourrier, V., & Lecavelier des Etangs, A. 2013, A&A, 557, A124
Brun, A., Miesch, M. S., & Toomre, J. 2004, ApJ, 614, 1073
Burrows, A., Sudarsky, D., & Hubbard, W. B. 2003, ApJ, 594, 545
Charbonneau, D., Brown, T. M., Noyes, R. W., & Gilliland, R. L. 2002, ApJ, 568, 377
Choudhuri, A. R., Schussler, M., & Dikpati, M. 1995, A&A, 303, L29
Cooper, C. S., & Showman, A. P. 2005, ApJL, 629, L45
Cranmer, S. R., & Saar, S. H. 2011, ApJ, 741, 54
Dobbs-Dixon, I., & Lin, D. N. C. 2008, ApJ, 673, 513
Ehrenreich, D., Bourrier, V., Bonfils, X., et al. 2012, A&A, 547, A18
Ekenbäck, A., Holmström, M., Wurz, P., et al. 2010, ApJ, 709, 670
Fortney, J. J., Marley, M. S., & Barnes, J. M. 2007, ApJ, 659, 1661
García Muñoz, A. 2007, P&SS, 55, 1426
Goldstein, M. L. 1978, ApJ, 219, 700
Heyvaerts, J., & Priest, E. R. 1983, A&A, 117, 220
Holmström, M., Ekenbäck, A., Selsis, F., et al. 2008, Nat, 451, 970
Hotta, H., Rempel, M., Yokoyama, T., et al. 2012, A&A, 539, A30
Huang, X., & Cumming, A. 2012, ApJ, 757, 47
Ito, H., Tsuneta, S., Shiota, D., Tokumaru, M., & Fujiki, K. 2010, ApJL, 719, 131
Kopp, R. A., & Holzer, T. E. 1976, SoPh, 49, 43
Kudoh, T., & Shibata, K. 1999, ApJ, 514, 493
Kurokawa, H., & Nakamoto, T. 2014, ApJ, 783, 54
Lammer, H., Selsis, F., Ribas, I., et al. 2003, ApJL, 598, L121
Landini, M., & Monsignori-Fossi, B.C. 1990, A&AS, 82, 229
Lecavelier des Etangs, A., Ehrenreich, D., Vidal-Madjar, A., et al. 2010, A&A, 514, A72
Linsky, J. L., Yang, H., France, K., et al. 2010, ApJL, 717, 1291
Madhusudhan, N., & Seager, S. 2009, ApJ, 707, 24
Madhusudhan, N., & Seager, S. 2010, ApJ, 725, 261
Matsumoto, T., & Kitai, R. 2010, ApJL, 716, L19
Matsumoto, T., & Suzuki, T. K. 2012, ApJ, 749, 8
Matsumoto, T., & Suzuki, T. K. 2014, MNRAS, 440, 971
Matthaeus, W. H., Zank, G. P., Oughton, S., Mullan, D. J., & Dmitruk, P. 1999, ApJL, 523, L93
Menou, K. 2012, ApJ, 745, 138
Muchmore, D. O., Nuth, J. A., III, & Stencel, R. E. 1987, ApJL, 315, L141
Murray-Clay, R. A., Chiang, E. I., & Murray, N. 2009, ApJ, 693, 23
Perna, R., Menou, K., & Rauscher, E. 2010, ApJ, 724, 313
Poppenhaeger, K., Schmitt, J. H. M. M., & Wolk, S. J. 2013, ApJ, 773, 62
Rogers, T. M., & Showman, A. P. 2014, ApJL, 782, L4
Sano, T., Inutsuka, S., & Miyama, S. M. 1999, in Astrophysics and Space Science Library, Vol. 240, Numerical Astrophysics: Proc. Int. Conf., Numerical Astrophysics 1998, ed. S. M. Miyama, K. Tomisaka, & T. Hanawa (Boston, MA: Kluwer), 383
Shiota, D., Tsuneta, S., Shimojo, M., et al. 2012, ApJ, 753, 157
Showman, A. P., & Guillot, T. 2002, A&A, 385, 166
Sorahana, S., Suzuki, T. K., & Yanamgura, I. 2014, MNRAS, 440, 3675
Sutherland, R. S., & Dopita, M. A. 1993, ApJS, 88, 253
Suzuki, T. K. 2007, ApJ, 659, 1592
Suzuki, T. K., & Inutsuka, S. 2005, ApJL, 632, L49
Suzuki, T. K., & Inutsuka, S. 2006, JGR, 111, A06101
Suzuki, T. K., Imada, S., Kataoka, R., et al. 2013, PASJ, 65, 98
Suzuki, T. K., & Inutsuka, S. 2006, JGR, 111, A06101
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