

Aeronomy of Extra-Solar Giant Planets at Small Orbital Distances

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ABSTRACT

One dimensional aeronomical calculations of the atmospheric structure of extra-solar giant planets in orbits with semi-major axes from 0.01 to 0.1 A.U. show that the thermospheres are heated to over 10000 K by the EUV flux from the central star. The high temperatures cause the atmosphere to escape rapidly implying that the upper thermosphere is cooled primarily by adiabatic expansion. The lower thermosphere is cooled primarily by radiative emissions from H_3^+ , created by photoionization of H_2 and subsequent ion chemistry. Thermal decomposition of H_2 causes an abrupt change in the composition from molecular to atomic near the base of the thermosphere. The composition of the upper thermosphere is determined by the balance between photoionization, advection, and H^+ recombination. Molecular diffusion and thermal conduction are of minor importance, in part because of large atmospheric scale heights. The energy-limited atmospheric escape rate is approximately proportional to the stellar EUV flux. Although escape rates are large, the atmospheres are stable over time scales of billions of years.

Subject headings: Extra-Solar Planets, Aeronomy, Atmospheric Escape

1. Introduction

Radial velocity observations and measurements of the dimming of light during transit events show that HD209458b is a Jupiter-like planet orbiting a sun-like star (Charbonneau *et al.* 2000, 2002; Henry *et al.* 2000). Spectroscopic observations during the transit have also detected the NaI D lines and the H Ly α line in absorption (Charbonneau *et al.* 2002; Vidal-Madjar *et al.* 2003), providing the first opportunity to observationally constrain the structure of an Extra-solar Giant Planet (EGP) atmosphere. The two spectroscopic detections to date probe different regions of the atmosphere. The apparent size of HD209458b, when viewed in the NaI lines, is only slightly larger than the apparent size of the planet at nearby wavelengths, suggesting that the observations probe a region in the troposphere of the planet, close to the cloud tops (Charbonneau *et al.* 2002). The apparent size of HD209458b in the H Ly α line is several planetary radii, implying that these observations

probe the upper most regions of an extended atmosphere (Vidal-Madjar *et al.* 2003).

The surprisingly large extent of the H cloud detected by Vidal-Madjar *et al.* (2003) implies that the scale height of the upper atmosphere is a significant fraction of a planetary radius. Yet, the skin temperature of an EGP at 0.05 AU is expected to be approximately 750 K (Goukenleuque *et al.* 2000; Sudarsky *et al.* 2003) whereas the gravitational acceleration of HD209458b is $\sim 900 \text{ cm s}^{-2}$, implying a scale height of $\sim 700 \text{ km}$, a value far too small to explain the observed H cloud. Thus, the existence of an extended H cloud implies that the upper atmosphere of HD209458b is at a much higher temperature than the lower atmosphere. Moreover, as on Jupiter, H_2 , not H, is the thermodynamically stable form of hydrogen at the temperatures and pressure of EGP atmospheres considered to date (Goukenleuque *et al.* 2000; Sudarsky *et al.* 2003). The existence of an extended H cloud implies either that the atmosphere is so hot that H is the stable species, or that

H is produced at a rapid rate by non-equilibrium processes. This paper investigates whether absorption of stellar EUV radiation in the upper atmosphere of an EGP can lead to the conditions implied by Vidal-Madjar *et al.*'s measurements. To this end, physical models of EGP upper atmospheric structure are constructed using techniques developed in studies of solar-system aeronomy. An improved understanding of the upper atmospheric structure of EGPs may also aid in their detection and characterization, by, for example, predicting other emission or absorption features or identifying preferred wavelength bands for extra-solar planet searches. Finally, the escape rate of the atmosphere is determined by conditions in the thermosphere; thus, the evolution of extra-solar planets may depend on their aeronomy. To date, there have been no thorough discussions of the aeronomy of EGP atmospheres, though several brief discussions of escape rates have appeared in the literature (Mayor and Queloz 1995; Burrows and Lunine 1995; Guillot *et al.* 1996; Vidal-Madjar *et al.* 2003).

Our investigation of the aeronomy of extra-solar planets is grounded in studies of Jupiter. Unfortunately, our understanding of the structure of Jupiter's thermosphere and ionosphere is not as robust as we would like. Measurements of the peak electron density in the Jovian ionosphere are often a factor of 10 less and occur at an altitude several scale heights above that predicted by photochemical models (McConnell and Majeed 1987). Measurements by the Galileo spacecraft indicate a complex situation with large temporal and spatial variations that have yet to be adequately interpreted. Suggestions for the discrepancies include a non-thermal H₂ vibrational distribution (Majeed and McConnell 1991; Cravens 1987) and thermospheric winds coupled with specific magnetic field geometries (McConnell and Majeed 1987; Matcheva *et al.* 2001), but these have yet to be verified and the problem is still without a clear resolution (Yelle and Miller 2003). Also, the thermospheric temperature on Jupiter is much higher than predicted by aeronomical models based on solar energy input and the heat source has yet to be confidently identified (Yelle and Miller 2003). The high temperatures may be due to dissipation of buoyancy or acoustic waves (Young *et al.* 1997; Matcheva and Strobel 1999; Hickey *et al.* 2000;

Schubert *et al.* 2003) or precipitation of energetic ions from the Jovian magnetosphere (Waite *et al.* 1997), or meridional transport of energy deposited in the auroral zones (Achilleos *et al.* 1998), or some combination of all three processes. In any case, our understanding of these processes is insufficient to support confident predictions about the thermospheric temperature of a gas-giant planet at large orbital distances.

Despite these difficulties, it is not unreasonable to apply aeronomical models to EGPs. Several factors suggest that the ionosphere of EGPs may be more easily understood than that of Jupiter. The thermospheric temperature of EGPs should be higher than that of Jupiter. This shortens chemical time constants, reducing the effect of winds. Also, higher temperatures should help equilibrate H₂ vibrational levels and make any non-thermal distribution less important. In addition, there is reason to hope that the thermospheric temperature on an EGP can be more easily understood than on Jupiter. Although it possible that wave heating or magnetospheric interactions dominate, it is reasonable to suppose that the primary energy source is the tremendous amount of stellar EUV radiation deposited in the EGP thermospheres. These conjectures need to be tested through observations, but they seem sufficient to justify a first look at the aeronomy of extra-solar giant planets.

2. Model Description

Calculations of the atmospheric structure on an EGP must be very general. In solar-system studies one can usually assume that the major atmospheric constituent is unaffected by chemistry, but, with the large amounts of energy deposited in their atmosphere, this may not be a safe assumption for EGPs. At the outset it is not clear if the dominant constituent is H₂ or H, created from dissociation of H₂, or H⁺, created by photoionization of H or H₂. Thus, chemical calculations must be capable of dealing with both neutral and ionized atmospheres and must dispense with the usual approach of calculating the chemistry of minor constituents in a background of a inert primary constituent. The calculations must treat all possible constituents in an equivalent manner. In addition, the temperature and composition of EGP thermo-

spheres are tightly coupled through the density of the radiatively active H_3^+ molecule; thus, the thermal structure and composition must be calculated self-consistently. Coupling between temperature and composition may also occur through heating efficiencies and thermal conduction rates that depend on composition and a species-dependent escape rate. Also, chemical reaction rates and diffusion rates depend on temperature and on EGPs the range of possible temperatures is so large that it may imply widely different consequences for composition.

This first investigation into the aeronomy of EGPs is based on one-dimensional (1D) models that are intended to simulate the global-average atmospheric structure. To calculate the average, all horizontal gradients and the horizontal velocities are assumed to be zero and the absorption rate of stellar EUV flux is averaged over all latitudes and local times, taking full account of the extended nature of the atmosphere. Comparison of 1D and 3D models for Titan’s thermosphere provide one validation of this approach (Müller-Wodarg *et al.* 2000). Of course, the rotation of an EGP is likely to be tidally locked to the central star so that the star-facing hemisphere is constantly illuminated and the opposite hemisphere in constant darkness. Some of the energy deposited on the illuminated hemisphere will be transported to the dark hemisphere, but large horizontal variations may still exist. It would be interesting to explore horizontal variations, but knowledge of the basic physical balances in the atmosphere is a prerequisite for such an investigation and this knowledge is best obtained with a 1D model.

The calculations presented here encompass the regions from $1 R_p$, where the pressure is 200 dyne cm^{-2} , to $3 R_p$; but the calculations are most accurate from a pressure of $\sim 1 \text{ dyne cm}^{-2}$ to $\sim 2 R_p$. The calculations neglect processes such as stratospheric chemistry and radiative transfer in molecular vibrational bands, that become important in Jupiter’s atmosphere at pressures greater than 1 dyne cm^{-2} . At distances of $\sim 2 R_p$ from the planet, stellar gravitation and stellar radiation pressure become important and gas densities become so low that the approximations implicit in the hydrodynamic equations become questionable. In this region, full solution of the Boltzmann is probably the best approach to calculations of

atmospheric structure. At the date of writing, neither chemical models for the stratosphere or kinetic models for the exosphere have been published. Eventually, it may be worthwhile to couple the thermospheric models described here to stratospheric and exospheric models in order to study the transition between regions in more detail. In the meantime, it is prudent to bear in mind that the models presented are most relevant for the thermosphere proper and are less accurate near the upper and lower boundary.

The results of Goukenleuque *et al.* (2000) are used as a guide to the the choice of conditions at the lower boundary. Although these calculations were carried out for 51 Peg b, the basic planetary parameters are similar enough to HD209458b so that the temperatures calculated by Goukenleuque *et al.* (2000) should be relevant. The Goukenleuque *et al.* (2000) calculations extend to 100 dyne cm^{-2} , and show that in this region the temperature is roughly constant and equal to the skin temperature of the planet, which is approximately 750 K. The calculations presented here have only a small temperature difference between 200 and 1 dyne cm^{-2} . The fact that the upper boundary of the stratosphere calculation and the lower boundary of the thermosphere calculation are both roughly isothermal suggests that only small errors are introduced by not modeling the transition accurately. Moreover, the calculated temperatures in the thermosphere are tens of thousands of kelvins higher than at the lower boundary, so errors or hundreds of kelvins near the base of the atmosphere are unimportant.

2.1. Composition

The composition is calculated by solving the 1D continuity and diffusion equations in spherical geometry

$$\frac{\partial N_j}{\partial t} = P_j - L_j N_j - \frac{1}{r^2} \frac{d}{dr} r^2 \Phi_j, \quad (1)$$

where for neutrals,

$$\Phi_n = u N_n - (1 - N_n/N) D_n \left[\frac{dN_n}{dr} + N_n \left(\frac{m_i g}{k T_n} + \frac{1}{T_n} \frac{dT_n}{dr} \right) \right], \quad (2)$$

and for ions,

$$\Phi_i = uN_i - (1 - N_i/N) D_i \left[\frac{dN_i}{dr} \right] \quad (3)$$

$$+ N_i \left(\frac{m_i g(r)}{kT_i} + \frac{T_e/T_i}{N_e} \frac{dN_e}{dr} + \frac{1}{T_i} \frac{d(T_e + T_i)}{dr} \right).$$

In equations (1-3), P_j is the production rate for the j th species, L_j the loss rate, N_j the volume number density, Φ_j the flux, D_j the diffusion coefficient, T_n the neutral temperature, g is the acceleration of gravity, T_i the ion temperature, T_e the electron temperature. N_e is the electron density, N the total density of the atmosphere, N_n is the density of the n th neutral species, and N_i is the density of the i th ion species. The quantity u is the vertical velocity of the atmosphere, defined as the mean velocity of the different constituents, weighted by their mass density.

It is assumed that, as on Jupiter, the homopause occurs at about $\sim 1 \text{ dyne cm}^{-2}$ so that heavy constituents such as CH_4 , CO , NH_3 , and H_2O are absent from the thermosphere. This is an essential assumption because it limits the species in the upper atmosphere to compounds that can be constructed from the lightest constituents. The models include the neutral species H_2 , He , and H , and the ionized species H^+ , H_2^+ , H_3^+ , He^+ , and HeH^+ . Table 1 lists the chemical reactions among these species. J -values are calculated assuming that the stellar output is similar to that of the Sun and using the solar spectrum of Woods *et al.* (1998). In addition to reactions commonly adopted in studies of Jovian aeronomy, Table 1 includes reactions that become important at high temperatures, such as thermal decomposition of H_2 (R4) and reaction of H^+ with vibrationally excited H_2 (R9). The rate for this latter reaction has not been measured and the value in Table 1 is estimated to be the product of the collision rate and the relative population of H_2 in the $v = 4$ state (Majeed and McConnell 1991).

Ions typically diffuse along magnetic field lines, whereas neutrals diffuse primarily in the radial direction. We have no information on the magnetic fields of EGPs and, moreover, are interested in globally-averaged models, and therefore assume that ion diffusion is also vertical. In addition, although the equations are written in their general forms, the calculations assume that $T_i = T_e = T_n = T$.

The densities of H_2 and He are held fixed at the lower boundary, where the He mole fraction is assumed to be 10%, similar to the Jovian value. Other species are assumed to be in chemical equilibrium at the lower boundary. The density gradient at the upper boundary for all species is calculated by assuming that each species has an upward velocity equal to its Jeans escape velocity. Initially, both neutrals and ions are assumed to escape at the Jeans rate, but subsequent models address the possibility that ions are prevented from escaping by a strong magnetic field. The escape of electrons is not considered explicitly, but rather the electrons and ions are assumed to escape together. This is modelled by reducing the ion mass by a factor of two in the calculation of the Jeans escape rate.

The molecular diffusion coefficient for the i th species is calculated from

$$\frac{1}{D_i} = \sum_j \frac{N_i N_j}{N b_{ij}}, \quad (4)$$

where b_{ij} is the binary diffusion parameter. For ion-ion and ion-neutral collisions, b_{ij} is calculated from the formulae in Banks and Kockarts (1973). Binary diffusion parameters for neutral-neutral collisions are obtained from Mason and Marrero (1970).

2.2. Thermal Structure

The thermal structure calculations include stellar energy deposition, thermal conduction, radiative emissions, advection, and adiabatic cooling. The temperature profile is obtained through solution of the energy balance equation

$$\rho c_p \frac{\partial T_n}{\partial t} - \frac{\partial p}{\partial t} = Q_\circ - Q_r + \frac{1}{r^2} \frac{d}{dr} r^2 \kappa \frac{dT_n}{dr} \quad (5)$$

$$- u \left(\rho c_p \frac{\partial T_n}{\partial r} - \frac{\partial p}{\partial r} - \frac{p}{m} \frac{\partial m}{\partial r} \right),$$

where p is the pressure, ρ is the mass density, c_p is the specific heat at constant pressure, m is the mean molecular mass of the atmosphere, and κ is the thermal conduction coefficient. Q_\circ is the heating rate due to absorption of stellar radiation, Q_r the cooling due to radiative emissions, the third term on the RHS represents the divergence of the thermal conduction flux, and the fourth term on the RHS represents the combined effects of work

TABLE 1
CHEMICAL REACTIONS

				Reaction					Rate ^a	Reference
R1a	H ₂	+	$h\nu$	\rightarrow	H ₃ ⁺	+	e		2.68×10^{-5}	Yan <i>et al.</i> (1998)
R1b				\rightarrow	H ⁺	+	H	+	8.93×10^{-7}	Yan <i>et al.</i> (1998)
R2	H	+	$h\nu$	\rightarrow	H ⁺	+	e		4.76×10^{-5}	Hummer and Seaton (1963)
R3	He	+	$h\nu$	\rightarrow	He ⁺	+	e		2.58×10^{-5}	Yan <i>et al.</i> (1998)
R4	H ₂	+	M	\rightarrow	H	+	H	+	$1.5 \times 10^{-9} e^{-48350/T}$	Baulch <i>et al.</i> (1992)
R5	H	+	H + M	\rightarrow	H ₂	+	M		$8.0 \times 10^{-33} (300/T)^{0.6}$	Ham <i>et al.</i> (1970)
R6	H ₂ ⁺	+	H ₂	\rightarrow	H ₃ ⁺	+	H		2.0×10^{-9}	Thread and Huntress (1974)
R7	H ₃ ⁺	+	H	\rightarrow	H ₂ ⁺	+	H ₂		2.0×10^{-9}	Estimated
R8	H ₂ ⁺	+	H	\rightarrow	H ⁺	+	H ₂		6.4×10^{-10}	Kapras <i>et al.</i> (1979)
R9	H ⁺	+	H ₂ ($v \geq 4$)	\rightarrow	H ₂ ⁺	+	H		$1.0 \times 10^{-9} e^{-21960/T}$	Estimated (see text)
R10a	He ⁺	+	H ₂	\rightarrow	HeH ⁺	+	H		4.2×10^{-13}	Schauer <i>et al.</i> (1989)
R10b				\rightarrow	H ⁺	+	H	+	8.8×10^{-14}	Schauer <i>et al.</i> (1989)
R11	HeH ⁺	+	H ₂	\rightarrow	H ₃ ⁺	+	He		1.5×10^{-9}	Bohme <i>et al.</i> (1980)
R12	HeH ⁺	+	H	\rightarrow	H ₂ ⁺	+	He		9.1×10^{-10}	Kapras <i>et al.</i> (1979)
R13	H ⁺	+	e	\rightarrow	H	+	$h\nu$		$6.3 \times 10^{-9} (300/T_e)^{0.64}$	Storey and Hummer (1995)
R14	He ⁺	+	e	\rightarrow	H	+	$h\nu$		$7.2 \times 10^{-9} (300/T_e)^{0.64}$	Storey and Hummer (1995)
R15	H ₂ ⁺	+	e	\rightarrow	H	+	H		$2.3 \times 10^{-8} (300/T_e)^{0.4}$	Auerbach <i>et al.</i> (1977)
R16a	H ₃ ⁺	+	e	\rightarrow	H ₂	+	H		$2.9 \times 10^{-8} (300/T_e)^{0.65}$	Sundström <i>et al.</i> (1994)
R16b				\rightarrow	H	+	H	+	$8.6 \times 10^{-8} (300/T_e)^{0.65}$	Datz <i>et al.</i> (1995)
R17	HeH ⁺	+	e	\rightarrow	He	+	H		$1.0 \times 10^{-8} (300/T_e)^{0.6}$	Yousif and Mitchell (1989)

^aTwo body rates are in cm^3s^{-1} and three body rates in cm^6s^{-1} . Photolysis rates (s^{-1}) are optically thin values at 0.05 AU. The solar spectrum of Woods *et al.* (1998) is used to represent the stellar EUV flux.

done by pressure and advection and is usually referred to as adiabatic cooling.

The stellar heating rate, Q_\circ includes contributions from exothermic reactions and energy transfer from energetic photoelectrons to the ambient atmosphere. Chemical heating rates for the reactions in Table 1 are calculated from heats of formation and are obtained from Lias *et al.* (1988). The chemical heating rate is not necessarily positive because both exothermic and endothermic reactions are important. For example, thermal decomposition of H₂ (R4) is endothermic by 436 kJ/mole; thus some of energy deposited in the atmosphere goes into dissociating H₂ rather than heating the atmosphere. Also, the chemical heating rates are not local because chemical species, particular H, can diffuse to other locations, where subsequent reactions convert chemical energy back into heat.

Photoelectrons lose energy to the ambient atmosphere through elastic and inelastic collisions with neutrals and through Coulomb collisions with ions and thermal electrons. The energy not transferred to the ambient atmosphere is lost to the planet through excitation of UV emissions, pho-

toelectron escape, etc. The models assumes that the extra energy acquired by the photoelectron in an ionization event is transferred to the ambient atmosphere with an efficiency of 63%. This value comes from the photoelectron transport calculation for a Jovian atmosphere in Waite *et al.* (1983). The value of 63% is probably not accurate for an EGP and should be viewed as a rough guess, but it is unlikely to be incorrect by more than tens of percent. More accurate estimates could be obtained with a photoelectron transport calculation, but the approach adopted here is sufficient for this first investigation of EGP aeronomy.

The important radiative emissions include IR radiation from H₃⁺ and radiation from H⁺ recombination. The H₃⁺ cooling rate is taken from Neale *et al.* (1996) and the H⁺ recombination cooling rate from Seaton (1960). The cooling rate is calculated by assuming optically thin emissions and neglecting absorption of radiation from the lower atmosphere. The results show that these approximations are accurate because optical depths are low and calculated thermospheric temperatures greatly exceed those in the lower atmosphere.

The thermal conduction flux can be carried ei-

ther by neutrals, ions, or electrons. On Jupiter the thermal conduction flux is carried primarily by neutrals, because the electron density is low. This may not be the case if an EGP has a robust ionosphere and neutral, electron, and ion conductivity must be allowed for. The electron conductivity is calculated from

$$\kappa_e = \frac{\kappa_{ei}}{1 + \kappa_{ei} \sum_k (1/\kappa_{en})}, \quad (6)$$

where the κ_{ie} term, due to electron-ion collisions, is given by

$$\kappa_{ei} = 1.2 \times 10^{-6} T_e^{5/2} \text{ erg cm}^{-1} \text{ s}^{-1} \text{ K}^{-1}, \quad (7)$$

and the κ_{in} term, due to electron-neutral collisions, is given by

$$\kappa_{en} = 1.2 \times 10^{-6} \frac{N_e}{N_n} T_e^{5/2} \text{ erg cm}^{-1} \text{ s}^{-1} \text{ K}^{-1}. \quad (8)$$

The ion conductivity is given by

$$\kappa_i = \frac{7.4 \times 10^{-8}}{\sqrt{\mu}} T_i^{5/2} \text{ erg cm}^{-1} \text{ s}^{-1} \text{ K}^{-1}, \quad (9)$$

where μ is the reduced mass for the ion-neutral collision. All of these expressions are obtained from Banks and Kockarts (1973). The neutral conductivity is calculated from

$$\kappa_n = \sum_j \frac{\kappa_j N_j}{\sum_k N_k \phi_k}, \quad (10)$$

where ϕ_k is the expression given in equation 14.33 of Banks and Kockarts (1973) and κ_j is the thermal conductivity of the j th constituent.

2.3. Momentum Balance

The vertical momentum equation is

$$\begin{aligned} \frac{\partial u}{\partial t} = & -u \frac{\partial u}{\partial r} - \frac{1}{\rho} \frac{\partial p}{\partial r} - g \\ & + \frac{1}{\rho} \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 2\mu \frac{\partial u}{\partial r} \right) - \frac{4\mu u}{\rho r^2}, \end{aligned} \quad (11)$$

where the first term on the RHS represents advection, the second term is the pressure gradient, the third term gravity, and the fourth and fifth, viscous deceleration of the gas. The quantity μ is the coefficient of viscosity.

After using the equation of state to related density and pressure, equation (11) can be integrated

to give the pressure in terms of gravity and the bulk velocity in steady-state

$$p(r) = p_o \exp \left(- \int \frac{GM}{R_g T} \frac{dr}{r^2} \right) \times (12)$$

$$\exp \left(- \int \frac{\partial u^2}{\partial r} \frac{dr}{2R_g T} \right) \times (13)$$

$$\exp \left(+ \int \left(\frac{2}{R_g T} \frac{\partial}{\partial r} \left(r^2 \mu \frac{\partial u}{\partial r} \right) - \frac{4\mu u}{R_g T} \right) \frac{dr}{r^2} \right),$$

where R_g is the gas constant. The first factor on the RHS of equation (12) represents the usual barometric variation of pressure, the second factor represents the effects of advection, and the third factor represents the effects of viscosity. The velocity can be obtained from the mass continuity equation and the mass density through

$$\rho u r^2 = \text{constant}. \quad (14)$$

The constant in this expression comes from the velocity at the upper boundary, which is set equal to the weighted average of the Jeans escape velocity of the individual constituents. Equations (12), (13), and the ideal gas law are then solved iteratively for consistent solutions of p , u , and ρ .

2.4. Numerical Method

The coupled momentum, energy, and continuity equations are solved by integrating to a steady state. The continuity equation is the first to be solved in each time step utilizing values for velocity and temperature from the previous time step. The energy equation is solved next, using the updated values for densities. The momentum equation is the last to be solved in each time step iteration, using the updated values for densities and temperature. The continuity equations for the individual species and the energy equation are solved using a fully implicit technique to advance to the next time step. As discussed above, the vertical momentum and mass continuity equations are solved together in iterative fashion, to find a steady state solution at each time step. The calculations are carried out on an altitude grid with equal spacing in R_p/R , which is a more natural coordinate for extended atmospheres than altitude itself. The atmosphere is divided into 300 layers from $1 R_p$, where the pressure is set to 200 dyne cm^{-2} , to $3 R_p$. The pressure at the upper boundary depends on the temperature profile, and varies from

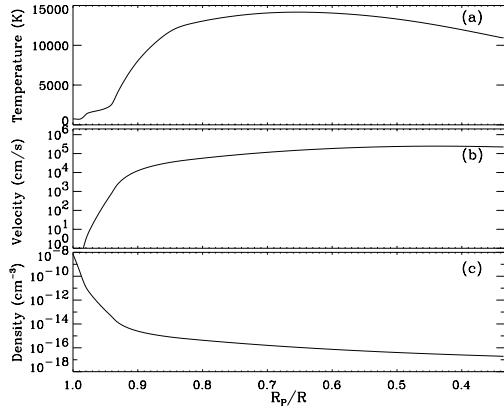


Fig. 1.— The altitude distributions of (a) temperature, (b) velocity, and (c) mass density for the reference model

10^{-5} to 5×10^{-4} dyne cm^{-2} for the range of models considered here. A time step of 1000 s is used to integrate to steady state. Calculations are run until all equations balance to better than 0.1% in all atmospheric layers.

3. Results

A reference model is described first in order to focus the discussion and facilitate an in-depth examination of the relevant physical balances prevailing in the atmosphere. The reference model used here adopts parameters similar to those of HD209458b, specifically a mass of $0.6 M_J$, a radius at 200 dyne cm^{-2} equal to $1.4 R_J$ and a star-planet distance of 0.05 AU . After discussion of the reference model, trends with changes in semi-major axes are considered in order to examine the range of plausible conditions in an EGP atmosphere and to investigate the sensitivity of atmospheric structure on the stellar EUV flux.

3.1. Reference Model

Figure 1 shows a summary of results for the reference model. The thermospheric temperature rises to values greater than 12000 K. This causes a greatly extended atmosphere with significant density to beyond $3 R_P$. The extent of the atmosphere is determined primarily by the λ parameter defined by

$$\lambda = \frac{GMm}{kTR} \quad (15)$$

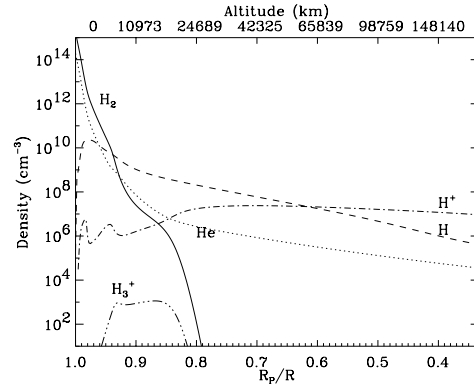


Fig. 2.— The composition of the reference model.

At the base of the atmosphere $\lambda = 313$, which is fairly close to the Jovian value of 474. However, at $3 R_P$, λ has decreased to 5.6, as a result of the high temperatures and lower gravity. The barometric pressure in an extended isothermal atmosphere in hydrostatic equilibrium varies as

$$p = p_0 e^{\lambda - \lambda_0}. \quad (16)$$

For small values of λ the decrease of pressure and density with distance is gradual, as shown in Fig. 2c. In fact, a value of $\lambda = 5.6$ at a pressure of 10^{-5} dyne cm^{-2} implies a pressure of 3.7×10^{-8} dyne cm^{-2} at $\lambda = 0$ or $r = \infty$. This is much greater than the pressure in interplanetary space, implying that the atmosphere can not be hydrostatic, but must be escaping in a manner similar to that of the solar wind. It is this fact that requires that the full vertical momentum equation be solved, rather than the usual hydrostatic approximation. The upward velocity of the atmosphere, shown in Fig. 1b, plays a critical role in the structure of EGP thermospheres and is one of the primary differences between the Jovian upper atmosphere and an EGP upper atmosphere.

The composition of the atmosphere is shown in Fig. 2 and the important chemical reactions for the reference model are shown in Fig. 3. Although the main species at the lower boundary are H_2 and He, the lower thermosphere is primarily H and the upper thermosphere H^+ . H_2 is quickly converted to H by thermal decomposition (R4). This process becomes important once the temperature reaches $\sim 2000 \text{ K}$. Photoionization makes only a minor contribution to the destruction of

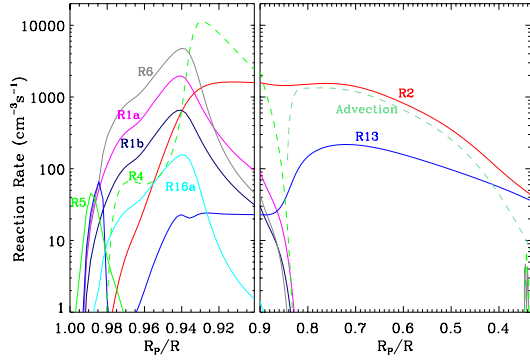


Fig. 3.— The primary chemical reaction rates in the reference model. Reaction R16b is not shown but is nearly equal to R6.

H_2 . The column-integrated H_2 destruction rate due to R4 is $4.0 \times 10^{12} \text{ cm}^{-2} \text{ s}^{-1}$, compared with $9.5 \times 10^{11} \text{ cm}^{-2} \text{ s}^{-1}$ for R1. The transition from H_2 to H strongly affects the atmosphere because the mean molecular mass drops by a factor of two and the scale height doubles. Helium also quickly disappears with increasing altitude because of diffusive separation. At higher altitudes, H^+ , becomes the dominant species, created by photoionization of H . The density of H^+ is regulated by an approximate balance between photoionization (R2) and advection. Loss of H or H^+ by diffusion is minor, partly because of the large scale heights in the atmosphere.

The calculated H_3^+ densities are relatively low. Partly, this is due to the rapid loss of H_2 and the resulting decrease in H_2 photoionization rates. An equally important process is the short lifetime of H_3^+ , which is related to the large electron density, associated with the high H^+ density. It is interesting that photoionization creates both H_2^+ , which is quickly converted to H_3^+ and H^+ and its associated electrons, which cause the ultimate destruction of H_3^+ . This leads to the somewhat surprising situation that an increase in the photoionization rate can cause a decrease in the H_3^+ density. The calculated H_3^+ density for the reference model is smaller than that in Jupiter’s ionosphere, typically calculated to be 10^4 - 10^5 cm^{-3} (Majeed and McConnell 1991). Despite its low density, it is shown below that H_3^+ plays a critical role in the thermal structure.

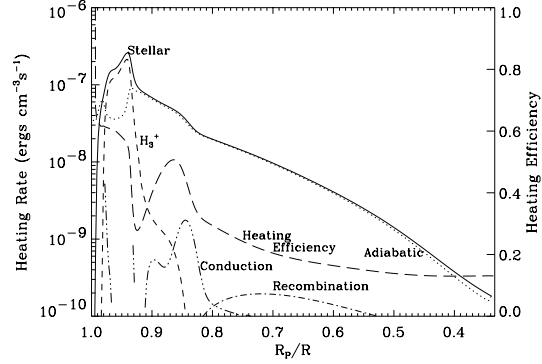


Fig. 4.— Heating rates and heating efficiencies in the reference model. The solid line represents the net heating rate in the atmosphere. Other terms represent cooling rates by the processes indicated.

The important terms in the energy balance equation are shown in Fig. 4. Stellar heating in the upper thermosphere is balanced primarily by adiabatic cooling. Cooling due to radiation and to the divergence of the thermal conduction flux is not significant. This differs from most planetary thermospheres where energy is carried away primarily by thermal conduction. The adiabatic cooling is a result of rapid atmospheric escape and is responsible for the gradual decrease in temperature with increasing distance above $R_p/R = 0.7$. Lower in the thermosphere, stellar energy deposition is balanced primarily by H_3^+ cooling. This is surprising considering the low H_3^+ densities, but H_3^+ is an effective coolant at high temperature (Neale *et al.* 1996). The weakness of thermal conduction is due to the large scale heights in the atmosphere. The rate of cooling due to thermal conduction varies roughly as κ/H_o^2 , where H_o is the scale height of the atmosphere; thus thermal conduction becomes less important as H_o becomes large.

Figure 4 also shows the heating efficiency, defined as the ratio of the net heating rate to the rate of stellar energy absorption. Low in the thermosphere, where the composition is primarily H_2 , the heating efficiency is 50-60%, consistent with that for the Jovian atmosphere (Waite *et al.* 1983). Higher in the thermosphere, the heating efficiency drops to $\sim 10\%$. This low value obtains because much of the absorbed stellar energy goes into ionizing H . This energy is either lost through escape

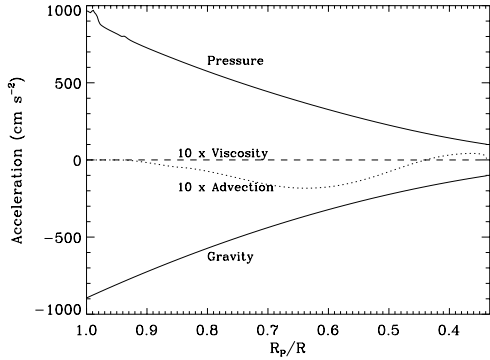


Fig. 5.— Accelerations in the reference model.

of H^+ or, upon recombination of H^+ the chemical energy is converted to radiant energy, i.e. a photon, that escapes the atmosphere. As a consequence, most stellar EUV energy absorbed by H escapes the atmosphere and does not contribute to local heating. This differs from recombination of H_2^+ or H_3^+ lower in the thermosphere, which returns chemical energy to the atmosphere through the kinetic energy of the reactant products.

Solution of the momentum equation reveals that the atmosphere is close to hydrostatic balance, despite the large escape rate. Figure 5 shows that gravitational acceleration is balanced primarily by the pressure gradient. Advection of momentum is minor, with a contribution less than 5% at all levels. Viscous forces are negligible. The dominance of hydrostatic balance is consistent with the fact that the velocity of the atmosphere, though large, is sub-sonic. The speed of sound at 12000 K is roughly 10 km s^{-1} , whereas the atmospheric velocity has a value at $3 R_p$ of 2.4 km s^{-1} . Thus, the velocity is large enough to have dominant effect on the temperature profile, but still has a minor effect on the density profile. Presumably, the planetary wind becomes supersonic at greater distances from the planet, but that region is not modelled here.

The momentum and energy balance in the atmosphere are coupled through the adiabatic cooling term. The dominance of the adiabatic cooling term in the upper thermosphere indicates that much of the stellar energy deposited in the atmosphere goes into lifting the atmosphere. Examination of the column-integrated rates confirm this

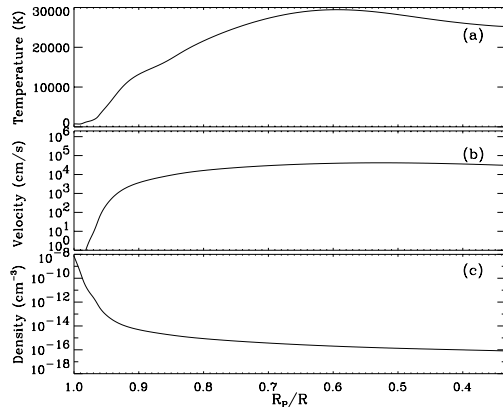


Fig. 6.— The same as Fig. 1 but for a model with ion escape inhibited.

conclusion. The column-integrated rates for stellar heating, H_3^+ cooling, and adiabatic cooling are 351 , 81 , and $267 \text{ erg cm}^{-2} \text{ s}^{-1}$, respectively, with radiative recombination and thermal conduction making up the small remainder. The adiabatic heating rate represents the energy required to raise thermospheric gases in the presence of a gravitational field. This term is zero in a static atmosphere and is therefore a direct consequence of rapid atmospheric escape. Thus, the energy balance indicates that most of the stellar energy deposited in the atmosphere goes into powering escape. This conclusion is supported by the variation of escape rate with stellar insolation, presented in section 3.3 below.

3.2. Inhibited Ion Escape

While neutrals are free to escape at the kinetic rate, ions may be inhibited from doing so by a planetary magnetic field. Presently, there is no evidence for or against an intrinsic magnetic field on EGPs, but, based on analogy with the Jovian planets, a strong field is a possibility. A magnetic field will inhibit ion escape as long as the magnetic pressure is greater than the plasma pressure. Because the flow is sub-sonic, the plasma pressure is due primarily to its thermal energy and the magnetic pressure is greater than the plasma pressure if

$$\frac{B^2}{8\pi} > N_i k T_i + N_e k T_e \quad (17)$$

The plasma pressure at the upper boundary of the reference model is $3.4 \times 10^{-5} \text{ dyne cm}^{-2}$. If an

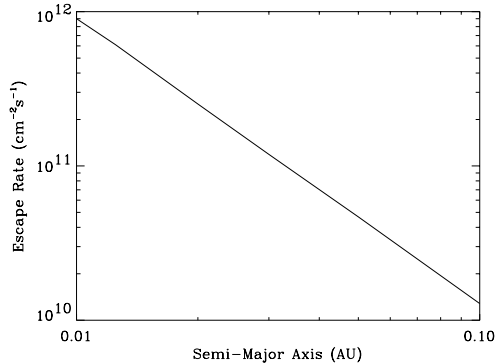


Fig. 7.— Escape rate versus semi-major axis

EGP has an intrinsic magnetic field strength at $1 R_p$ of 4.3 gauss (the Jovian value), then the magnetic pressure is $0.74 \text{ dyne cm}^{-2}$, more than sufficient to confine the plasma. If the plasma pressure were constant with radial distance the plasma and magnetic pressures would balance at $37 R_p$. Of course, at sufficiently high magnetic latitudes, the B field lines of an EGP should be open to the stellar wind, allowing ions to escape by flowing along the field lines. Where this occurs depends on the interaction between the stellar wind and the EGP magnetosphere and, based on experience with the planets in our solar system, this is likely to be a complex interaction. Full investigation of this area is outside the scope of this paper, but some insight into the potential effects of a magnetic field can be gained by considering the simple situation where neutrals escape at the kinetic rate, but ions are inhibited from escaping.

The results from such a model are shown in Fig. 6. Inhibiting ion escape reduces the bulk velocity of the atmosphere from 2.2 km s^{-1} at $3 R_p$ in the reference model to 0.4 km s^{-1} in the model with inhibited ion escape. The lower velocity reduces the amount of adiabatic cooling leading to temperatures about 10,000 K higher in the inhibited ion escape model than the reference model. As a consequence, the densities at high altitudes are roughly a factor of 5 larger in the model with inhibited ion escape than in the reference model. However, the net escape rate with ion escape inhibited is only $\sim 30\%$ smaller than in the reference model because the higher temperatures and densities cause an increase in the H escape rate

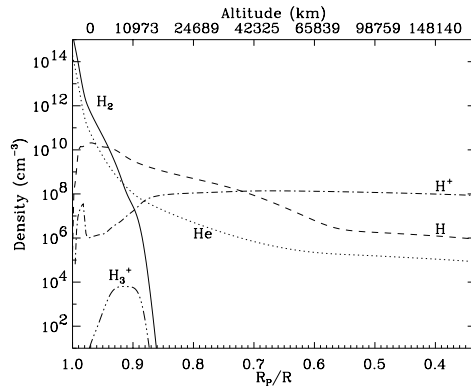


Fig. 8.— Predicted composition for a semi-major axis of 0.01 AU

that compensates for the decrease in the H^+ escape rate.

3.3. Trends with Semi-Major Axis

The nature of atmospheric escape from an EGP can be explored further through examination of trends with semi-major axis. Figure 7 shows the calculated escape rate as a function of distance from the central star for an assumed circular orbit. The calculations assume that both neutrals and ions escape at the kinetic rate. The ratio of escape rates for $a = 0.01$ and $a = 0.05$ AU is a factor of 20, only 20% less than the ratio of incident stellar flux, thus the escape rate varies roughly as the stellar flux. This indicates that the escape rate is energy limited, i.e. the escape flux is not determined by the temperature of the atmosphere, but by the amount of stellar EUV energy absorbed in the upper atmosphere. The existence of an energy limit to the escape rate was first postulated by (Watson *et al.* 1981) and the concept was subsequently applied to models of the early atmosphere of Venus (Kasting and Pollack 1983) and to models of Pluto's atmosphere (Hunten and Watson 1982; McNutt 1989; Hubbard *et al.* 1990; Krasnopolsky 1999). In all of these examples the planetary winds are strongly supersonic. The interesting point here is that the energy limit also applies for a milder wind, that is only a fraction of the speed of sound.

Figures 8 and 9 show the composition for models calculated with $a = 0.01$ and 0.1 AU. As ex-

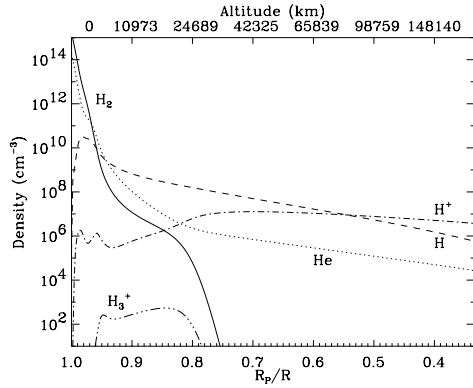


Fig. 9.— Predicted composition for a semi-major axis of 0.1 AU

pected, higher insolation increases the abundance of H^+ relative to H and pushes the H_2 – H transitions to lower altitudes. The H_3^+ densities are about a factor of ten larger in the $a = 0.01$ AU model than in the $a = 0.1$ AU model, varying approximately as the square root of the ionization rate. Figure 10 shows the temperature profiles for a variety of semi-major axes from 0.01 to 0.1 AU. The maximum temperatures increase by only a factor of ~ 2 for the factor of 100 variation in the stellar heating rate. This is because the increase in adiabatic cooling associated with the larger escape rates offsets the larger heating rate for the close-in models. The increased importance of adiabatic cooling can be seen in the stronger negative temperature gradient at high altitudes in the $a = 0.01$ AU model.

Figures 11 and 12 show the energy balance for the $a = 0.01$ and 0.1 AU models. The primary difference between the $a = 0.01$ AU model and the reference model is the importance of recombination cooling in the $a = 0.01$ model. This is somewhat counter intuitive because it might be thought that the larger escape rate in the $a = 0.01$ might lead to stronger adiabatic cooling. However, at smaller star-planet distances the ionization fraction is larger because of the increase in ionization rate, implying an increase in the recombination rate. This effect dominates over the increase in adiabatic cooling making recombination and adiabatic cooling of comparable importance at $3 R_p$ and making recombination cooling the dominant term near $2 R_p$. As with the refer-

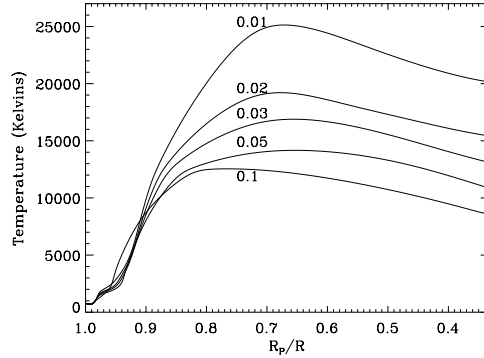


Fig. 10.— Temperature profiles for a variety of planet-star distances. Semi-major axes in AU are indicated on the figure.

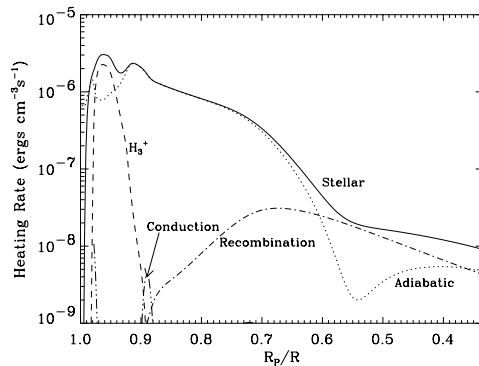


Fig. 11.— The same as Fig. 4 but for the $a = 0.01$ AU model.

ence model, H_3^+ cooling dominates from 1 to $1.1 R_p$ in the $a = 0.01$ AU model and thermal conduction is of minor importance at all altitudes.

Based on the discussion in the previous paragraph one would expect adiabatic cooling to dominate over recombination cooling in the $a = 0.1$ AU model and Fig. 12 shows that this is in fact the case. Recombination cooling is of marginal importance in this model. Thermal conduction is relatively more important in the $a = 0.1$ AU model, contributing roughly 10% of the net cooling from 1.07 to $1.25 R_p$.

Figure 13 shows the momentum balance for the $a = 0.01$ AU model. The larger velocity of the atmosphere causes vertical advection to become an

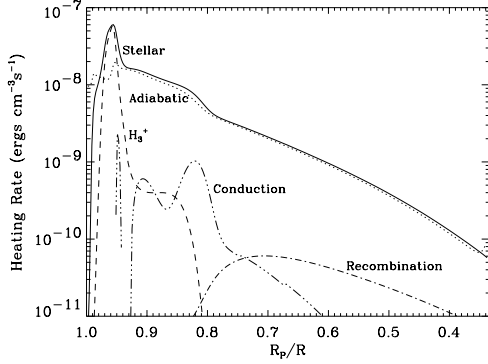


Fig. 12.— The same as Fig. 4 but for the $a = 0.1$ AU model.

important term in the momentum balance equation and the atmosphere is no longer close to hydrostatic equilibrium. Momentum balance for $a = 0.1$ AU is not shown because both viscosity and advection are negligible and the atmosphere is in hydrostatic balance to high precision.

4. Discussion

There is a qualitative agreement between the hot thermospheres calculated here and the H Ly α absorption measurements of Vidal-Madjar *et al.* (2003). The observed absorption signature has a magnitude of $\sim 15\%$. In the visible, the planet occults about 1% of the star light, so an absorption of 15% implies that H is optically thick to about $4R_p$. The reference model has an H density of $4.1 \times 10^5 \text{ cm}^{-3}$ at $3R_p$ and a temperature of 10909 K, implying a tangential column abundance of $1.7 \times 10^{16} \text{ cm}^{-2}$. Assuming a Maxwell-Boltzmann distribution for the H cloud and using the temperature quoted above implies an absorption cross section at Ly α line center of $5.6 \times 10^{-14} \text{ cm}^2$ and an optical depth of ~ 1000 . Thus, the H distribution calculated here is opaque out to several planetary radii, in rough agreement with the measurements. Vidal-Madjar *et al.* (2003) also show that the absorption extends roughly 0.5 \AA from the center of the Ly α line. This only occurs if the H distribution is characterized by a high temperature. Assuming a Maxwell-Boltzmann distribution and a temperature of 10,000 K implies a Doppler broadened

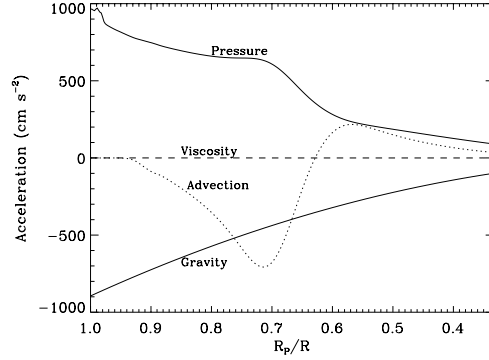


Fig. 13.— The same as Fig. 5 but for the $a = 0.01$ AU model.

absorption line with a width of 0.055 \AA . An optical depth at line center of 1000 implies that optical depth unity is reached roughly 3 Doppler widths from line center or at 0.16 \AA . This is of the same order but somewhat smaller than measured by Vidal-Madjar *et al.* (2003).

A more quantitative comparison requires improvements to the models. As mentioned earlier, the assumptions contained in these aeronomical models become questionable at a distance of $3R_p$ from the planet. The gravitation field of the central star and radiation pressure can no longer be neglected and a 1D calculation is no longer possible. Instead it is preferable to construct kinetic models that calculate the H distribution by integrating along trajectories in the exosphere.

The Vidal-Madjar *et al.* (2003) observations demonstrate the utility of investigating the atmospheres of EGPs through the H Ly α absorption technique. It is also worthwhile to consider if there are other diagnostic spectral features that could be used to study the upper atmosphere of an EGP. The upper atmosphere of Jupiter has been investigated through analysis of emissions in the UV and near IR. Jovian H_3^+ emissions in the near IR have been a particularly useful probe of upper atmospheric temperatures and ion densities. H_3^+ is absent in stellar atmospheres and any detected emissions could safely be assumed to originate from an EGP. The H_3^+ distribution in an EGP thermosphere is probably best studied with the ‘‘occultation spectroscopy,’’ technique discussed by Richardson *et al.* (2003). Essentially,

this consists of comparing the flux measured from the star-planet system with the EGP in front of and behind the central star. The advantages of H_3^+ are that the emissions are characterized by a high temperature, occur in a wavelength regions where the star is relatively dim, and extend a significant distance about the nominal radius of the EGP, the criteria mentioned by Richardson *et al.* (2003) as defining good candidate emissions for occultation spectroscopy. A mitigating factor is that the H_3^+ density is low and the emissions are optically thin. The reference model predicts an H_3^+ emission rate of $82 \text{ erg cm}^{-2}\text{s}^{-1}$. For HD209458b at a distance of 47 pc and a radius of $1.4 R_J$, this implies a flux at the Earth of $9.7 \times 10^{-20} \text{ ergs cm}^{-2}\text{s}^{-1}$. Detailed simulations are needed to determine if emissions at this level could be detected with occultation spectroscopy.

An EGP should also be bright in Lyman and Werner band emissions and again these emissions have the advantage that they do not occur in the stellar spectrum. The Jovian upper atmosphere has been studied through analysis of UV emissions in the H_2 Lyman and Werner electronic band systems, as well as $\text{H Ly}\alpha$ and H_3^+ emissions. Adopting a wavelength-integrated disc brightness of 2 kR for the Jovian emission and scaling by the planet-star distance implies a brightness of $2 \times 10^4 \text{ kR}$ and a flux at Earth of $\sim 10^{-8} \text{ photons cm}^{-2}\text{s}^{-1}$ for HD209458b, assuming that emissions come from half the visible hemisphere of the EGP.

The H_2 Lyman and Werner band emissions could be larger than implied by scaling the Jovian emission rate. For example, auroral emissions may exist in addition to dayglow emissions. On Jupiter, the auroral emissions in the H_2 Lyman and Werner bands are brighter than the disc-integrated emission (Yelle and Miller 2003). In addition, fluorescent excitation of the Lyman band emissions from an EGP atmosphere may be more efficient than on Jupiter. Most of the Lyman and Werner band fluorescence from Jupiter's thermosphere occurs from the ground vibrational state of H_2 because the relatively cool temperatures imply low populations of vibrationally excited molecules. The higher temperatures in an EGP atmosphere imply a higher level of vibrational excitation. This is important because it becomes possible to absorb $\text{Ly}\alpha$ radiation in the P(5) and R(6) lines of the Lyman (1,2) band. $\text{H Ly}\alpha$ is by far the bright-

est line in the FUV spectrum of solar-type stars and absorption of this line implies much higher fluorescent intensities than would otherwise obtain. Elevated H_2 Lyman band emissions due to $\text{H Ly}\alpha$ fluorescence was observed on Jupiter after the Shoemaker-Levy 9 collisions, which caused an elevation in the temperatures of the Jovian thermosphere (Wolven *et al.* 1997). A possible advantage to the study of Lyman and Werner band emission is that the stellar background at FUV wavelengths is relatively low. More detailed examination of the H_2 Lyman and Werner band emissions from EGP atmosphere will be presented in a future publication.

The results reported here are also of interest to investigations of the evolution of EGPs. Vidal-Madjar *et al.* (2003) have suggested that the escape rate from an EGP may be large enough to affect the evolution of the planet. The calculations presented here do not support this conclusion. The escape rate for the reference model is $\sim 5 \times 10^{10} \text{ cm}^{-2}\text{s}^{-1}$, about 100 times smaller than inferred by Vidal-Madjar *et al.* (2003), and corresponds to a mass loss rate of 10^5 kg s^{-1} . This implies that only 3×10^{-6} of the mass of the planet is lost in 1 Gyr. A mass loss rate this low should have an insignificant effect on the evolution of the planet. The Vidal-Madjar *et al.* value is derived from the observed $\text{H Ly}\alpha$ absorption signature, rather than from escape calculations but few details on the derivation are given in Vidal-Madjar *et al.*'s brief report and further investigation is required to determine if in fact the two results are inconsistent.

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