ELSEVIER

Available online at www.sciencedirect.com
ScienceDirect

Planetary and Space Science 55 (2007) 1426–1455

Planetary and Space Science

www.elsevier.com/locate/pss

Physical and chemical aeronomy of HD 209458b

A. García Muñoz[1]

Department of Earth and Space Science and Engineering, York University, Toronto, ON, Canada M3J 1P3

Received 10 March 2006; received in revised form 13 March 2007; accepted 21 March 2007
Available online 3 April 2007

Abstract

We report on the physical and chemical aeronomy of the hot Jupiter HD 209458b, a prominent case in the growing sample of known extrasolar planets. Our work is motivated by the recent detections of hydrogen, carbon and oxygen atoms obscuring about one tenth of the disk of the host star at the detection wavelengths and which have been interpreted as evidence for an escaping atmosphere. We model the escape and composition of the irradiated atmosphere by solving the equations of mass, momentum and energy conservation. At an orbital distance $a\sim0.05$ AU, intense Extreme Ultraviolet stellar irradiation may lead to the massive escape of its atmosphere. It is shown that for a planet of the characteristics of HD 209458b at small enough orbital distances, tidal forces may enhance the escape rate over the $1/a^2$ law inferred from simple energetic arguments, shortening the lifetime of the planet to a few Gigayears. This conclusion is contingent upon the premise of supersonic escape, on which we have based our calculations. It is expected that the atmosphere of HD 209458b contains hydrogen, helium and trace amounts of heavier elements such as carbon, oxygen and nitrogen. Indeed, the observations indicate that some of the heavier species reach as far above the surface of the planet as the lighter hydrogen atoms. We evaluate the abundances of the likely species forming from these elements and from the deuterium isotope throughout the upper atmosphere. Beyond a few planetary radii, all elements are strongly ionized, the atoms of carbon, helium and nitrogen being the first to do so. Our model, in the scenario of solar abundance for heavy constituents appears to be consistent with the observation depths of the three detected atoms. We have implemented a mass-consistent treatment of molecular and ambipolar diffusion suitable for multi-temperature multi-component gases that can be readily implemented in the modelling of planetary atmospheres.

Keywords: Extrasolar planets; Hot Jupiters; Aeronomy; Atmospheric escape; Composition of atmospheres; Molecular and ambipolar diffusion

1. Introduction

The year 1995 marked the first instance of a planet detected orbiting a main-sequence star beyond our solar system (Mayor and Queloz, 1995). Since then, the number of these objects has increased to about 200, and is certain to keep growing in the coming years as more efforts are committed to the systematic tracking of target stars. The radial velocity survey of stars has provided the majority of the discoveries of extrasolar planets to date. This technique selectively favours the detection of massive bodies with short orbital periods that can perturb their host stars more sensitively. Thus, it is not at all unreasonable that the sample of currently known extrasolar planets contains a significant number of planets with masses $M_{\mathrm{P}}\sin i$ (M_{P} is the planetary mass and i is the inclination of the planetary orbit) of about 1 M_{J} (index $_{\mathrm{J}}$ refers to Jovian properties) in orbits of semi-major axes $a\leqslant0.1$ AU. Exceptionally, some of these planets have been observed while transiting the disk of their host stars. At the time of writing this, Schneider (The Extrasolar Planet Encyclopaedia, http://exoplanet.eu/) reports 10 transiting planets. The dimming of the light received from the star in conjunction with radial velocity measurements has made it possible to infer their orbital inclinations, radii and absolute masses, revealing mean planetary densities comparable to those of Jupiter and Saturn (Sozzetti et al., 2004). This result has led to the conviction that the nature of these planets is that of gas giants composed of hydrogen, helium and trace amounts of other heavier constituents (Burrows et al., 2001). Their mere existence has challenged the theories of planetary formation. In the core accretion theory, gas giant

---

E-mail address: agm121@rsphysse.anu.edu.au.

[1] Now at the Research School of Physical Sciences and Engineering, The Australian National University, Canberra, ACT 0200, Australia.

0032-0633/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.pss.2007.03.007

planets are thought to form far from their host stars, where lower temperatures and the relatively abundant residual matter facilitate the formation of gaseous massive bodies. Even though these planets may have migrated from their birth places, a hypothesis that would reconcile theory and discoveries, many unknowns remain as to the evolution and stability of these planetary systems (Perryman, 2000). For their statistical weight in the sample of known extrasolar planets, massive close-in planets have deserved a denomination of their own. They are often referred to as 'hot Jupiters'. The understanding of the formation and evolution of hot Jupiters could inform us about the prospects of finding terrestrial-like planets where life-supporting conditions may have taken root. Disciplines such as aeronomy, which is the focus of this work, are also expected to benefit from the new discoveries. At small orbital distances, intense irradiation is expected to drive the atmospheres of hot Jupiters into conditions unknown to our contemporary solar system.

The few positive identifications of atmospheric constituents on hot Jupiters have occurred by means of transmission spectroscopy. This method probes the limb of the planet during transits in search of wavelength-specific absorption signatures. Long path lengths at the limb facilitate the detectability of the less abundant species. The first measurement in the atmosphere of an extrasolar planet was the detection of neutral sodium at 589.3 nm on HD 209458b from the Hubble Space Telescope by Charbonneau et al. (2002). The observations exhibited a relative dip of $0.0232 \pm 0.0057\%$ by sodium absorption and were thought to probe the lower atmosphere of the planet. Shortly after, Vidal-Madjar et al. (2003) reported a total $15 \pm 4\%$ absorption of stellar Lyman-α photons by neutral hydrogen in the atmosphere of the same planet. The 15 % absorption, notably larger than the ratio of planetary to stellar surfaces $(R_\mathrm{p}/R_\star)^2 \sim 1.5\%$, suggested an optically thick hydrogen cloud surrounding the planet and extending to a few planetary radii above its visible surface. Later HST observations confirmed the detection of hydrogen and revealed that carbon and oxygen are additional constituents of the gas cloud. Absorptions of $5 \pm 2\%$ (over the entire Lyman-α line), $7.5 \pm 3.5\%$ and $13 \pm 4.5\%$ were reported for atoms of hydrogen, (ionized) carbon and oxygen by Vidal-Madjar et al. (2004). Failed attempts at detecting CO at 2.3 μm from the Earth's atmosphere with the Keck II telescope have been reported by Brown et al. (2002) and Deming et al. (2005a). Other efforts to discern absorption signatures of He atoms at 1.083 μm (Moutou et al., 2003) have not as yet met with success.

Occultation spectroscopy offers an alternative way of probing the atmosphere of a planet by comparing the combined stellar plus planetary spectrum before and as the secondary eclipse occurs. This method has been tried on HD 209458b from the Infrared Telescope Facility at 2.3 μm (Richardson et al., 2003a), from the Very Large Telescope at 3.6 μm (Richardson et al., 2003b) and from the Spitzer Space Telescope at 24 μm (Deming et al., 2005b). The latter work has provided the first signals of IR thermal emission from this planet. Also with the Spitzer Space Telescope, other positive observations of thermal emission are those by Charbonneau et al. (2005) at 4.5 and 8 μm of TrES-1 and the 16 μm observations by Deming et al. (2006) of HD 189733b. The emitted thermal radiation bears the mark of the constituents, clouds and haze in the atmosphere. The comparison of model emission spectra with experimental spectra should help detect new atmospheric species. The CO, H_2O and CH_4 molecules, which are expectedly abundant and have strong absorption bands in the IR, are particularly good candidates.

The effective temperature, T_eff, is an indicator of the global energy budget in a planetary atmosphere. Assuming that only a fraction $1 - \Lambda$ of the stellar energy available at an orbital distance a, $\sigma T_\star^4 (R_\star/a)^2$, is intercepted by the planet, and that this energy is reradiated from the entire globe ($f = 1$) or from part of it ($f > 1$) as from a black body, the effective temperature of the atmosphere can be expressed as

$$T_\mathrm{eff} = T_\star (f(1 - \Lambda))^{1/4} \left(\frac{R_\star}{2a} \right)^{1/2}. \qquad (1)$$

The stellar effective temperature $T_\star$ and the stellar radius $R_\star$ are magnitudes known for a large number of stars. The Bond albedo Λ is a parameter specific to each planet, but typically small for the planets of our solar system. In the case of HD 209458b, photometry from the MOST satellite between 4000 and 7000 Å has allowed Rowe et al. (2006) to estimate the upper limit $\Lambda \leqslant 0.375$, which is consistent with an effective temperature $T_\mathrm{eff} \geqslant 1300$ K. Burrows et al. (2001) estimate effective temperatures between 1000 and 1500 K for the hot Jupiters reported prior to that year. The temperature of an equivalent black body whose emission at the observation wavelength matches the measured radiation flux is termed the brightness temperature at the corresponding wavelength. The IR thermal emission measurements of Deming et al. (2005b), Charbonneau et al. (2005) and Deming et al. (2006) have confirmed the predictions of elevated temperatures on hot Jupiters with reported brightness temperatures of 1010 ± 60 K at 4.5 μm, 1230 ± 60 K at 8 μm, 1117 ± 42 K at 16 μm and 1130 ± 150 at 24 μm.

Other recent efforts to detect atmospheric constituents have focused on the H_3^+ ion, that emits intensely at various bands between 2 and 4 μm, with, as of yet, negative results (Haywood et al., 2004; Shkolnik et al., 2006).

The recent detections of hydrogen, carbon and oxygen in the upper atmosphere of HD 209458b have prompted a renewed interest in the mechanisms of rapid escape from planetary atmospheres. The atmospheres of hot Jupiters may receive enough stellar energy to cause substantial atmospheric escape that, if extended over long time spans, could shorten significantly the lifetime of the gaseous envelope of the planet. Watson et al. (1981) set up the problem of a hydrogen neutral atmosphere that undergoes