Part III

Structure and atmospheres of planets

Planetary Systems in the Universe - Observation, Formation and Evolution
Proceedings IAU Symposium No. 202, ©2004 IAU
Alan Penny, Pawel Artymowicz, Anne-Marie Lagrange, & Sara Russell, eds.

New Insights into Extrasolar Giant Planets

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Abstract. In this contribution, I summarize recent theoretical attempts to understand important diagnostic aspects of close-in extrasolar giant planets, in particular transits and albedos. The potential scientific returns of the anticipated direct detection of "EGPs" in transit and/or in reflection are significant.

1. New Worlds

Defined as objects found using the high-precision radial-velocity technique around stars with little or no intrinsic variability and previously thought to be without companions, the ~60 extrasolar giant planets (EGPs; Burrows et al. 1995) that have been discovered to date span more than two orders of magnitude in $m_p \sin(i)$, semi-major axis, and period (Butler et al. 1997,1998; Cochran et al. 1997; Delfosse et al. 1998; Fischer et al. 1999; Henry et al. 2000; Korzennik et al. 2000; Latham et al. 1989; Marcy and Butler 1996; Marcy et al. 1998; Marcy et al. 1999; Marcy, Butler, and Vogt 2000; Marcy, Cochran, and Major 2000; Mayor and Queloz 1995; Mazeh et al. 2000; Noyes et al. 1997; Queloz et al. 2000; Santos et al. 2000; Udry et al. 2000; Vogt et al. 2000; and references therein). Collectively, EGPs show the wide range of eccentricities typical of stellar companions, while those within ~0.07 A.U. have the small eccentricities expected for objects that have experienced significant tidal dissipation. There is an interesting excess of primaries with super-solar metallicities, as yet unexplained. Multiple EGPs are known in a few systems (*e.g.*, 55 Cnc, υ And) and this number is sure to grow as measurements extend to longer orbital periods and known velocity residuals are patiently followed.

EGP surface temperatures (inferred from semi-major axes, stellar luminosities, ages, Bond albedos, and EGP masses) range from ~200 K for distant EGPs to ~1600 K for the close-in EGPs (Marley et al. 1999; Sudarsky, Burrows, and Pinto 2000). Though there is a selection bias for close-in planets in short-period orbits and though "Jupiters" with longer periods (11.9 years) would not as yet have been detected, the properties of this growing family of EGPs could not be more unexpected. However, we can not now distinguish between true EGPs (planets) and brown dwarfs. The inclination angles for most of the radial-velocity objects are unknown; some "EGPs" are bound to be much more massive than Jupiter and to be brown dwarfs on the tail of a "stellar" population of companions. Importantly, for semi-major axes less than ~4.0 A.U., there is a dearth of objects with $m_p \sin(i)$s above 10 M_J (Marcy and Butler 1998); such a population would easily have been detected if it existed (Marcy and Butler

1998). This implies that most of the "EGPs" are in the class of true planets distinct from higher-mass brown dwarfs and that the latter, if companions, are preferentially found at larger orbital distances.

Certain theoretical subtopics (such as transit and albedo studies) are emerging as particularly intriguing and timely. Hence, we review the theory of these subtopics and explore the physics and chemistry upon which they depend.

2. Close-in EGPs: "Roasters"

Close-in EGPs can attain temperatures and luminosities that rival those of stars near the main-sequence edge, despite the fact that the latter can be ~50–100 times more massive (Guillot et al. 1996; Burrows et al. 2000). Although the brown dwarf Gliese 229B is 10–50 times as massive as the EGP 51 Peg b, they have similar effective temperatures. Moreover, stellar irradiation can swell the radii of such short-period gas giants by 20% to 80%, thereby enhancing the magnitude and probability of the photometric dip during a planetary transit (*e.g.*, HD209458b: Charbonneau et al. 1999, Henry et al. 2000; Mazeh et al. 2000, Jha et al. 2000, Brown et al. 2000).

Hence, the most interesting, unexpected, and problematic subclass of EGPs are those found within ~0.1 A.U. of their primaries, 50–100 times closer than Jupiter is to our Sun. At such orbital distances, due to stellar irradiation alone, an EGP can have an effective temperature greater than 600 K. Indeed, the EGPs HD187123b, HD209458b, τ Boo b, HD75289b, 51 Peg b, υ And b, and HD217107b (Mayor and Queloz 1995; Marcy and Butler 1995; Butler et al. 1997, 1998; Fischer et al. 1999; Henry et al. 2000; Charbonneau et al. 2000) likely all have $T_{\rm eff}$s above 1000 K. This is to be compared with $T_{\rm eff}$s for Jupiter and Saturn of 125 K and 95 K, respectively. Despite such proximity, these planets are stable to tidal stripping and significant evaporation (Guillot et al. 1996).

Charbonneau et al. (1999) and Cameron et al. (1999,2000) were able to constrain the geometric albedo of the "roaster," τ Boo b, to be below ~0.3 (~0.48 μm) and ~0.22 (0.4 μm to 0.6 μm), respectively, and have shown that techniques even today are tantalizingly close to having the sensitivity required for direct detection. The recent discovery that one of the close-in EGPs, HD209458b, does indeed transit its star has provided a first-of-its-kind measurement of an EGP's radius and mass and a glimpse at what one will be able to learn once a family of these systems is found.

2.1. The Transit of HD209458

The HD209458b transits were the first stellar transits by a planet with an atmosphere to be observed in over a century. The transits of the F8V/G0V star HD209458 (at a distance of 47 parsecs) by HD209458b last ~3 hours (out of a total period of 3.524 days) and have a depth of ~1.5-2.0%. The ingress and egress phases each last ~25 minutes (Charbonneau et al. 2000; Henry et al. 2000). The properties of the planet, in particular its orbital distance and radius, scale with the properties of the star and values for the planet's radius (R_p) around ~1.4 R_J have been quoted (Henry et al. 2000; Charbonneau et al. 2000; Mazeh et al. 2000; Jha et al. 2000), with the most precise value, $1.347 \pm 0.060 R_J$, derived from HST/STIS photometry (Brown et al. 2000).

With the availabilility of such a precise photometrically-derived radius, the question naturally arises: what physical processes determine the transit radius and to what pressure level does it pertain? Several physical processes in an EGP's atmosphere are potentially important for determining the transit radius: Rayleigh scattering, refraction, molecular absorption, and cloud scattering. Hubbard et al. (2001) find that molecular absorption dominates all other mechanisms, at least in the optical and near IR. In agreement with the predictions of Seager and Sasselov (1998), due to variations in the molecular absorption cross sections with wavelength, the transit radius is a function of wavelength. In the region which determines the HST/STIS transit radius, the atmosphere is estimated to have a temperature of $\sim$1000 K and where the slant optical depth is unity the pressure is $\sim$10 millibars.

Large radii for close-in EGPs were predicted by Guillot et al. (1996). Importantly, since HD209458b transits its primary, astronomers can derive $\sin(i)$ ($i \sim 86.7^\circ$), from which the planet's mass ($\sim$0.69 M_J) can be directly determined. The ability to pin down more than one structural parameter for a given EGP is a milestone in the emerging study of extrasolar planets and a harbinger of what can be expected as the list of known close-in EGPs grows.

As Zapolsky and Salpeter (1969) demonstrated for planets made of high-Z material, any planet with a cold radius larger than $\sim$0.75 R_J must be made predominantly of hydrogen. Using the ANEOS equation of state tables, Burrows et al. (2000) derive that an "olivine" (rock) or H_2O (ice) planet with a mass of 0.69 M_J has a radius of 0.31 R_J or 0.45 R_J, respectively. Importantly, these radii are 3–4 times smaller than observed for HD209458b and prove that HD209458b must be a hydrogen-rich gas giant; it cannot be a giant terrestrial planet or an ice giant such as Neptune or Uranus.

Burrows et al. (2000) also found that HD209458b's large radius is not due to mere thermal expansion of its atmosphere ($\sim$1%), but is due to the high residual entropy that remains throughout its bulk by dint of its early proximity to the luminous primary. The large stellar flux does not inflate the planet, but retards its otherwise inexorable contraction from a more extended configuration at birth. Essentially, irradiation flattens the temperature profile at the top of the convective zone, while at the same time moving the radiative/convective boundary inward. Since radiative fluxes are governed by the product of thermal diffusivities and temperature gradients and since the thermal diffusivity decreases with increasing pressure, the flux of energy out of the convective core and the rate of core entropy change are reduced. The upshot is a retardation of the contraction of the planet. High stellar fluxes on a close-in EGP can have profound structural consequences. In particular, stellar insolation can be responsible for maintaining the planet's radius at a value 20% to 80% larger than that of Jupiter itself (Burrows et al. 2000).

There is a great difference between the theoretical radius of an isolated and of an irradiated EGP. Since the scale-height effect is miniscule, the R_p–t trajectory of the isolated EGP immediately suggests that if HD209458b were allowed to dwell at large orbital distances ($\geq$0.5 A.U.) for more than a few$\times 10^7$ years, its observed radius could not be reproduced (Burrows et al. 2000). It is at such ages that the radius of an isolated 0.69-M_J EGP falls below HD209458b's observed radius. This implies either that such a planet was formed near its current orbital distance or that it migrated in from larger distances ($\geq$0.5 A.U.), no later than a few times 10^7 years of birth. This is the first derived constraint on the history of an EGP and suggests the potential power of coupled transit and evolutionary studies.

2.2. EGP Albedos

The theoretical study of EGP albedos and reflection spectra is still largely in its infancy. Marley et al. (1999) explored a range of EGP geometric and Bond albedos using temperature-pressure profiles of EGPs in isolation (*i.e.*, no stellar insolation), while Goukenleuque et al. (2000) modeled 51 Peg b in radiative equilibrium and Seager and Sasselov (1998) explored radiative-convective models of EGPs under strong stellar insolation. The theoretical reflection spectra generated by Goukenleuque et al. (2000) and by Seager, Whitney, and Sasselov (2000) are particularly informative.

Sudarsky, Burrows, and Pinto (2000, hereafter SBP) recently attempted to establish a general understanding of the systematics of the albedo and reflection spectra of EGPs, tying them to their overall compositions and clouds. For those preliminary calculations, SBP defined five representative composition classes based loosely on $T_{\rm eff}$. The classification of EGPs into five composition classes, related to $T_{\rm eff}$, is instructive, since it can be shown that the albedos of objects within each of these classes exhibit similar features and values. The "Jovian" Class I objects ($T_{\rm eff} \leq 150$ K) are characterized by the presence of ammonia clouds and gaseous methane. In somewhat warmer objects ($T_{\rm eff} \geq$ 250 K), ammonia is in its gaseous state, but the upper troposphere contains condensed H_2O. These objects are designated Class II, or "water cloud," EGPs and also contain a large abundance of gaseous methane. Class III, or "clear" EGPs, are so named because they are too hot ($T_{\rm eff} \geq 500$ K) for significant H_2O condensation and so are not expected to contain any principal condensates. Absorption by gaseous water, methane, molecular hydrogen (via CIA), and neutral alkali metals, together with the absence of dominating cloud layers, give Class III EGPs the lowest Bond and geometric albedos of any class. In hotter EGPs (900 K $\leq T_{\rm eff} \leq$ 1500 K; Class IV) the troposphere is expected to contain significant abundances of absorbing neutral sodium and potassium gases above a silicate cloud layer and the albedo will be low. However, the hottest ($T_{\rm eff} \geq 1500$) and/or least massive EGPs with low gravities ($g \leq 10^3$ cm s^{-2}) have a silicate layer located so high in the atmosphere that much of the incoming radiation is reflected back out into space before being absorbed by neutral alkali metals or molecules (Seager and Sasselov 1998). SBP designated these highly reflective EGPs Class V. Hence, SBP concluded that neither the Bond nor the geometric albedos of EGPs are monotonic with $T_{\rm eff}$. For instance, around a G2V star, the Bond albedos are $\sim$0.5, $\sim$0.8, $\sim$0.1, and $\sim$0.55 for Classes I through V.

Direct photometric and spectroscopic detection of close-in EGPs is likely within the next few years. The SBP set of EGP albedos serve as a useful guide to the prominent features and systematics over a full range of EGP effective temperatures, for $T_{\rm eff}$s from $\sim$100 K to 1700 K. However, full radiative (and evolutionary) modeling of a given EGP at a specific orbital distance from its central star (of given spectral type), and of specific mass, age, and composition is necessary for a detailed understanding of a particular object.

Acknowledgments

The author thanks Bill Hubbard, Jonathan Lunine, Mark Marley, Didier Saumon, Tristan Guillot, David Sudarsky, and Christopher Sharp for informative exchanges, as well as NASA for its financial support via grants NAG5-7073 and NAG5-7499.

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