

EXTRASOLAR GIANT PLANETS UNDER STRONG STELLAR IRRADIATION

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ABSTRACT

We investigate irradiation of extrasolar giant planets (EGPs) by treating the radiative transfer in detail, so that the flux from the parent star interacts with all relevant depths of the planetary atmosphere with no need for a preassumed albedo. Rayleigh scattering (in dust-free models) increases the EGP's flux by orders of magnitude shortward of the Ca II H and K doublet (3930 Å), and the spectral features of the parent star are exactly reflected. The inclusion of dust increases the reflected flux in the blue. In the optical and near-IR, the thermal absorption of the planet takes over, but the absorption features are changed by the irradiation.

Subject headings: planetary systems — radiative transfer — stars: atmospheres — stars: low-mass, brown dwarfs

1. INTRODUCTION

Within the past 2 years, detection of planets orbiting Sun-like stars has exploded. To date, nine have been detected, four of which orbit amazingly close to their parent stars: less than 0.1 AU, which is 4 times closer than Mercury is to the Sun. These include 51 Peg b (Mayor & Queloz 1995), 55 Cnc b, τ Boo b, and ν And b (Butler et al. 1997). A more distant yet still close-in extrasolar giant planet (EGP), ρ CrB b at 0.23 AU, was detected by Noyes et al. (1997). Because these planets are being bombarded by intense radiation from their parent stars, their spectra and temperature structures are radically altered compared to planets at Jupiter-like distances from their parent stars.

There is a strong need to theoretically model the close-in EGPs' atmospheres because, ironically, they may be the first of the extrasolar planets to be detected directly. The flux emitted from EGPs represents only a small fraction of the flux of the parent star at any wavelength. However, because of dust formed high in their atmospheres, the close-in EGPs' reflected light in the optical may add significantly to the observed flux, which may be enough to make the EGPs directly detectable. For example, R. W. Noyes (1998, private communication) has developed a spectral separation technique that uses the Doppler shift of the spectrum of the primary and takes advantage of the large orbital velocity of the close-in EGPs. With reflected light, close-in EGPs may be bright enough for spectral separation. In addition, models of close-in EGPs are needed for evolutionary and interior calculations, which are critically sensitive to the detailed treatment of the planetary atmosphere.

Recent work on spectral modeling, colors, interior modeling, and evolution of EGPs and brown dwarfs (BDs) (e.g., Burrows et al. 1997; Allard, Alexander, & Hauschildt 1998) has been extremely successful. So far there have been only limited attempts at stellar irradiation modeling. Due to the intense radiation field from the nearby star, the atmospheres of close-in EGPs must be treated by detailed radiative transfer solutions, which is a new problem for planetary physics. In particular, planets have outer convection zones, while close-in EGPs develop outer radiative zones because of the strong external heating, which inhibits convection (Guillot et al. 1996). The first models for irradiated EGPs were calculated by Saumon et al. (1996) and for close-in EGPs by Guillot et al. (1996). They assumed for simplicity that the EGPs reflect the light of the parent star like a graybody, that the thermal emission of the

EGP is that of a blackbody, and that a fraction (with a Bond albedo equal to 0.35) of the flux from the parent star is absorbed by the planet. Their calculations also reveal the large sensitivity of the EGPs to the amount of irradiation.

In this Letter, we present model atmosphere calculations of the effects of strong irradiation on an EGP with particular emphasis on the issues involved in treating irradiation accurately. As an illustration, we compute preliminary models for the EGP orbiting τ Boo.

2. THE ATMOSPHERE MODEL

Our model atmosphere code is of a type common to irradiation modeling of close binary stars. The generic version was developed by Nordlund & Vaz (1990) for binary stars with $T_{\text{eff}} = 4500\text{--}8000$ K and in plane-parallel geometry. Our code is made suitable for much cooler temperatures in the equation of state and opacities. We use the simplifying assumption of LTE and the mixing length theory for convection. The angle- and frequency-dependent radiative transfer equation is solved for an atmosphere with a plane-parallel structure, using the Feautrier method. Our equation of state includes the following: up to two ionization stages of the elements H, He, C, N, O, Ne, Na, Mg, Al, Si, S, K, Ca, Cr, Fe, Ni, and Ti; the ions H^- , H_2^+ , and H_2^- ; and the molecules H_2 , H_2O , OH, CH, CO, CN, C_2 , N_2 , O_2 , NO, NH, C_2H_2 , HCN, C_2H , HS, SiH, C_3H , C_3 , CS, SiC, SiC_2 , NS, SiN, SiO, SO, S_2 , SiS, and TiO. The molecular dissociation constants are from Tsuji (1973). We include bound-free and free-free atomic opacities from Mathisen (1984), Thomson scattering, and Rayleigh scattering by H_2 and H. We also include straight means opacities of H_2O (Ludwig 1971) and TiO (Collins & Fay 1974), which are the dominant optical and infrared molecular opacities for $T_{\text{eff}} = 1500\text{--}2000$ K.

Our model atmosphere is sufficient for a preliminary investigation into the problem of close-in EGPs because we are investigating the main effects of stellar irradiation; we are more concerned with the correct treatment of radiative transfer of the incoming radiation than a chemically complete model atmosphere.

3. MODEL ATMOSPHERES FOR CLOSE-IN EGPs

3.1. *The Radiative Transfer*

The radiative transfer problem involves the plane-parallel radiation field of the parent star reaching the upper boundary

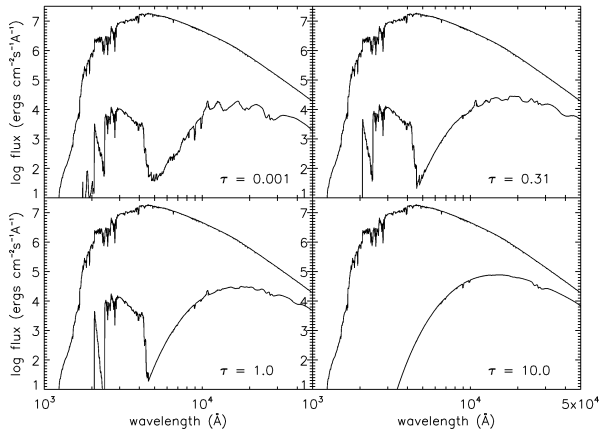


FIG. 1.—Dust-free planetary surface flux at different optical depths for τ Boo b for a Rosseland mean optical depth scale. The upper curve in each frame is the surface flux of τ Boo A. The reflected features in the near-UV are formed low in the atmosphere, where the density of H_2 is highest.

of the EGP atmosphere and propagating into it. The atmosphere of the planet can be treated as plane parallel; the radiative transfer inside it is essentially a one-dimensional problem with angle dependence to the normal to the surface. The equation of transfer is then written as a second-order differential equation with two-point boundary conditions. It can be solved using Feautrier's method (e.g., Mihalas 1978), which accounts explicitly for scattering terms and the two-point boundary conditions—recovering the diffusion approximation inner boundary and allowing a simple condition for the upper boundary. The solution can also treat neighboring frequencies with very different opacities.

Three changes to the Feautrier method are required in order to treat irradiation of an atmosphere: (1) change of the upper boundary condition to allow incident radiation from the parent star; (2) in addition to the angular dependence to the normal to the surface of the planet, an angular dependence of the upper boundary condition to the azimuthal angle about the normal to the surface with respect to the direction of the incident flux, i.e., the incident radiation is not necessarily in the same plane as the planet's outgoing radiation; and (3) accounting for the different angular dependence of the incoming from the outgoing radiation, i.e., the radiation is incoming from a specific direction for only some of the same angles as the outgoing radiation. These last two changes allow for the phases to be correctly calculated, although for this Letter we have assumed that we are viewing the planet in a gibbous phase and we have treated the irradiation as flux from the parent star, i.e., the star's intensity averaged over angle. This small improvement will be addressed in a later paper. In general, stellar atmosphere codes that allow incoming radiation, e.g., MULTI (Carlsson 1992) and PANDORA (Avrett & Loeser 1992), do not consider the second two issues because they intend to treat incoming radiation from their own atmosphere, the corona, where the incoming radiation is only present for the same directions and angles and in the same plane as the outgoing radiation.

The radiative transfer solution with the azimuthal boundary condition remains essentially the same as the Feautrier method described above, with the incident and outgoing intensities treated at all appropriate depths. The radiation temperature of the incoming radiation is not vastly different (parent stars are solar-like) from that of the close-in EGP, hence very little frequency reprocessing of radiation occurs. Solving for the incident-specific intensity involves frequency-dependent pro-

cesses of absorption, emission, and scattering and means no preassumed albedo is needed. Heating is determined by competing processes: absorption processes (bound-bound, bound-free, free-free) destroy a photon, and the photon's energy contributes to the thermal energy of the gas at the depth at which the photon of that frequency was absorbed; scattering processes (by atoms, molecules, dust, etc.) do not contribute to the kinetic energy of particles in the gas and decouple the radiation field from local conditions. This detailed radiative transfer approach is equivalent to a detailed albedo calculation. However, the reverse is not true: model atmosphere calculations that use albedos (even frequency-dependent ones), instead of detailed radiative transfer calculations such as described in this Letter, generate inaccurate temperature profiles and emergent spectra because the reflection and heating from irradiation is a complex function of frequency and depth. In addition, the reflected light cannot easily be separated from heating or the planet's internal flux. For example, the monochromatic albedo, which we define as the ratio of reflected planetary flux to incident flux at a specific frequency, is as high as 0.45 around 2400 Å. In the optical it is less than 0.04, even in our models that include dust (see § 4). However, this number does not illustrate the strong heating of the planet, which is not included in reflected light.

Figure 1 shows how the radiation penetrates to different optical depths depending on frequency. The scattered line formation in the UV range (in the absence of dust) from H_2 Rayleigh scattering occurs very low in the atmosphere, where the density of H_2 is highest. In the TiO frequency range, some of the incoming radiation is absorbed at a much higher position in the atmosphere, where the TiO opacity is strongest. At $T_{\text{eff}} = 1580$ K in this example, in the absence of dust clouds the incoming radiation in the UV will penetrate far more deeply than the radiation in the infrared, which is absorbed high in the planetary atmosphere.

3.2. Conservation of Entropy

In standard stellar atmospheres, flux constancy (of the total radial energy flux) of all relevant sources is often used to derive the temperature stratification $T(\tau)$, where τ is the optical depth. In a one-dimensional model calculation of an irradiated planet, we need to abandon total flux constancy locally in order to conserve entropy at the bottom of the convection zone. Entropy conservation is required because the illuminated and nonilluminated atmospheres are two sides of the same planet and the interior of both sides will be in the same thermodynamic state. We assume that this is the case for the close-in EGPs, although its accuracy still needs to be determined. Conservation of entropy at the bottom of a deep convection zone is a common approach in irradiation modeling (e.g., Vaz & Nordlund 1985). If the irradiation penetrates deeply enough to affect the temperature at the upper boundary of the convection zone, the effect on the overall structure of the atmosphere [e.g., $T(\tau)$] is magnified by the requirement of entropy conservation compared to flux conservation. This illustrates the need to compute the propagation of the incident radiation field inside the planet's atmosphere.

3.3. Temperature Structure Dependence on Radiative Transfer Methods

In the current literature, effective temperatures (T_{eff}) of close-in EGPs are estimated as the equilibrium effective temperature T_{eq} at a given distance from the primary star using an assumed albedo of the planet and the luminosity of the primary star (Guillot et al. 1996): $T_{\text{eq}} = T_*(R_*/2D)^{1/2}[f(1-A)]^{1/4}$. Here the

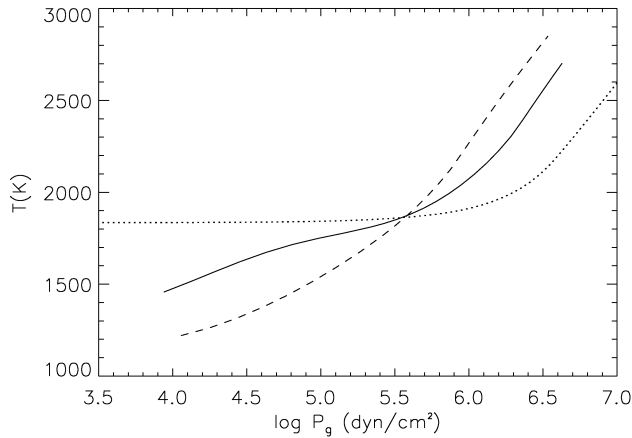


FIG. 2.—Comparison of temperature distributions in the surface layers of a dust-free model with $T_{\text{eff}} = 1835$ K. Two different distributions result from external irradiation—a fixed external boundary condition model with T_{eq} (dotted line) and our detailed radiative transfer model (solid line). They are compared to a BD atmosphere (same T_{eff}) with no incident external radiation (dashed line). See § 3.3 for more details.

asterisk subscripts refer to the parent star, D is the distance of the planet from the parent star, $f = 1$ if the heat is evenly distributed, and $f = 2$ if only the heated side reradiates the energy. Physically, T_{eq} is the temperature attained by a non-conducting, nonreflecting unit area perpendicular to the incident flux and located at a distance D from the parent star. Because T_{eq} is independent of the radius and mass of the planet (dependent only in a complicated manner through the yet unknown albedo), this definition reflects the planet's distance from the parent star more than quantifying the planet's net flux. During the evolution of an irradiated planet or for a very massive close-in object, $T_{\text{eff}} > T_{\text{eq}}$ because of the planet's internal flux. While the above equation is a good starting approximation for T_{eff} , more accurate T_{eff} estimates need to be calculated by irradiated model atmospheres and interior calculations.

Irradiation can be treated by different methods. Guillot et al. (1996) and Saumon et al. (1996) use T_{eq} as the upper boundary condition of the model atmosphere. A solution would match this imposed upper boundary temperature in a local (diffusion approximation) manner. For more details, see Guillot & Morel (1995). In this way, all of the radiation is locally coupled to—and heats—the atmosphere, with the heat deposited at the surface ($T = T_{\text{eq}}$) and propagated inward in the gray (constant opacity), diffusion approximation manner. This method overestimates the change in the temperature gradient compared to the physical situation because all incoming radiation is transferred to heat high in the atmosphere. However, even in the simplest case of an irradiated gray atmosphere, the temperature stratification is a complex function of optical depth and incident angle (Vaz & Nordlund 1985). In the detailed radiative transfer treatment that we use, some of the radiation will be scattered without heating the atmosphere. In addition, the nonblackbody irradiation will penetrate and heat different depths depending on frequency-dependent absorbers in the planetary atmosphere. If the radiation propagates fairly deeply (as shown in Fig. 1), the entire temperature structure is significantly changed by the requirement of entropy conservation.

The different outcomes are shown for a $T_{\text{eff}} = 1835$ K planet/BD in Figure 2, which compares the temperature structures of (a) an isolated planet/BD, (b) an irradiated planet (our detailed radiative transfer), and (c) an irradiated planet with the diffusion approximation method. Such different temperature distributions

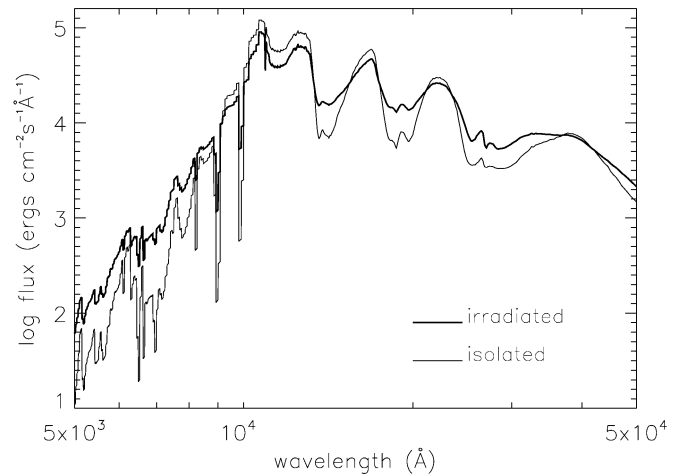


FIG. 3.—Emergent spectra (surface flux) for $T_{\text{eff}} = 1835$ K dust-free models of an isolated BD (thin curve) and an irradiated planet/BD (thick curve) at the position of τ Boo b. The two spectra correspond to the temperature distributions (dashed and solid lines, respectively) shown in Fig. 2.

strongly affect the emergent spectral features (as shown in Fig. 3).

3.4. Dust

The strong scattering and absorbing properties of dust will strongly affect the atmospheres of close-in EGPs, depending on the location of the dust, which usually results in more reflected light in the optical and near-IR. Ideally, three-dimensional radiative transfer should be used to compute the dust scattering accurately, especially since the dust species have very different optical properties in three dimensions whereas in one dimension, the optical profiles of different dust species may be very similar to each other. Of further importance to the atmosphere problem, but not unique to close-in EGPs, dust will “steal” away atoms from the absorbing molecules such as TiO (Tsuji, Ohnaka, & Aoki 1996) and in turn reduce their opacities and change the temperature structure.

While our model atmospheres code does not incorporate grain formation, we illustrate the effect of silicate dust on the reflection properties of the EGP by using the equilibrium condensation range for MgSiO_3 described in Lunine et al. (1989) and scaling its abundance by that of Mg. We use the Mie theory for opacities (as described in Ivezić, Nenkova, & Elitzur 1998) averaged over all angles, with the interstellar dust grain size distribution as described in Kim, Martin, & Hendry (1994) (the grain size distribution in EGPs/BDs is unknown). The optical properties of the silicates are taken from Ossenkopf, Henning, & Mathis (1992).

Figure 4 shows the effect of dust, where it has reflected spectral features of the parent star in the optical. For some wavelengths, reflection is superposed on absorption features. In this case, the dust reflection dominates the TiO opacity. With the equilibrium condensation method, very little silicate dust forms, but still enough forms to reflect the incident radiation. While we have taken into account the reduction of TiO due to O in the silicates, the small amount of dust formation leaves the TiO and H_2O opacities unaffected. Without dust, scattering in the optical will be minimal, resulting in little reflected light, as shown by the lower spectrum in Figure 4 (thick line).

While we do not attempt to address the complex issue of dust formation, it should be noted that because of irradiation, the close-in EGPs are much hotter than the observed brown

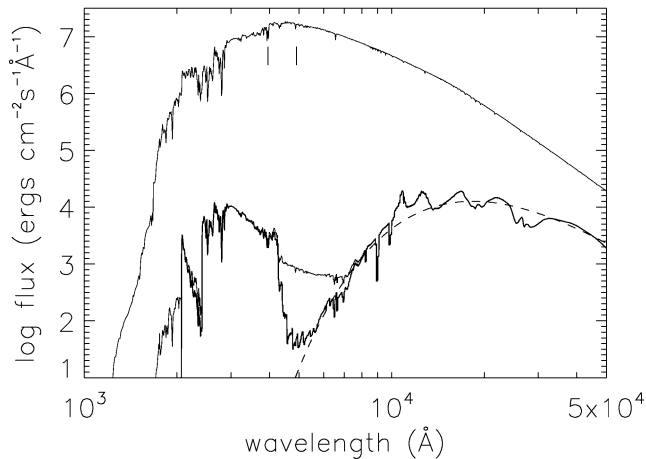


FIG. 4.—Low-resolution spectrum (reflected + thermal) of τ Boo b (lower thick solid curve), compared to that of τ Boo A (upper curve). Plotted are surface fluxes. The lower thin solid curve is τ Boo b with silicate dust formation, where the reflected spectral lines of the primary can be seen shortward of $H\beta$ (4860 Å). The short vertical line on the right is $H\beta$, and the one on the left is the Ca II H and K doublet; both are seen as reflected features in the planet. Here τ Boo b has $T_{\text{eff}} = 1580$ K and $R_b = 1.2R_j$; τ Boo A has a radius $R_A = 1.2 R_{\odot}$. The dashed line is a 1580 K blackbody.

dwarf Gliese 229B, and Marley et al. (1998) suggest that there will not be abundant condensates for the temperature range in which all close-in EGPs fall. In general, while model atmospheres that incorporate dust formation (Allard et al. 1998; Burrows et al. 1998; Tsuji et al. 1996) have been very successful so far, many obstacles remain. Some that are discussed in Allard et al. (1998), Burrows et al. (1997), and Lunine et al. (1989) include accurate dust formation, unknown grain shape and size distribution, possible clumpy distribution of grains in the atmospheres, and time-dependent dynamics that remove grains from the upper photosphere over short timescales.

4. EMERGENT SPECTRUM FOR A CLOSE-IN EGP

As an example of a close-in EGP, we use τ Boo b (Butler et al. 1997), a planet with mass $M\sin i = 3.87M_j$ and at a distance of 0.0462 AU from its parent star. There are many uncertainties about the close-in EGPs, such as mass, radius, gravity, composition, T_{eff} , etc. We have chosen only one example out of a large range of parameter space: $M = 3.87M_j$, $T_{\text{eff}} = 1580$ K, $\log g$ (cgs) = 4.0, and solar metallicity. The incident flux of τ Boo A (F7V, $T_{\text{eff}} = 6600$, metallicity [Fe/H] = +0.28, and $\log g$ (cgs) = 4.5; Gonzalez 1997) was taken

from the model grids of Kurucz (1992). Figure 4 shows the emergent spectrum of τ Boo b and τ Boo A.

We find the following interesting differences from an isolated EGP:

1. In the spectrum of τ Boo b (Fig. 4), the identical reflected spectral features from τ Boo A appear in the near-UV region. In this frequency range, H_2 Rayleigh scattering dominates over any absorption, and the result is exact frequency-matched reflected light. Where absorption and scattering are comparable, reflected features from the parent star are seen on top of the absorption features from the planet (e.g., from 2065–2410 Å in Fig. 4). The abrupt rise in flux below wavelength 4220 Å is likely due to the wavelength dependence of the Rayleigh scattering ($\sim\lambda^{-4}$), although our opacities are incomplete in that wavelength range. The existence of silicate dust will result in more reflected light, as shown in Figure 4, especially at optical wavelengths.

2. In wavelength regions of effective scattering, the total (emitted + reflected) flux of τ Boo b is increased by roughly 1–3 orders of magnitude compared to an isolated planet/BD with the same T_{eff} of 1580 K. The larger the temperature difference between the planet and the parent star, the more pronounced the increase.

3. In an irradiated planet, the TiO and H_2O absorption features are shallower and broader due to the reduced temperature gradient in the upper atmosphere. Figure 3 shows a comparison of the emergent spectra for an irradiated and for an isolated planet/BD, both with $T_{\text{eff}} = 1835$ K.

5. CONCLUSION

This first Letter on spectrum formation in close-in EGPs shows that strong irradiation results in a radically altered temperature structure and change in absorption features as compared to an isolated EGP with the same T_{eff} . Because spectral features, including reflection from dust, are highly sensitive to irradiation, model atmospheres of close-in EGPs must treat the incident radiation accurately with no need for a preassumed albedo. This is especially relevant for detection techniques (e.g., R. W. Noyes 1998, private communication) that use a narrow range of frequency and detailed information about high-resolution line shapes.

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