WHAT IF EXTRASOLAR PLANETS ARE ROCKY?. D. E. Trilling and H. J. Melosh, *Lunar and Planetary Lab, University of Arizona, Tucson, AZ 85721, trilling@lpl.arizona.edu*.

The recent discoveries (Mayor & Queloz 1995; Marcy & Butler 1996; Butler & Marcy 1996; Butler et al. 1997; Cochran et al. 1997; Noyes et al. 1997) of extrasolar giant planets in very close orbits to their stars have raised many interesting questions in planetary science. In this work, we consider the possibility that these planets are rocky, not gaseous like Jupiter is, and consider what the surface temperatures and heat flows of these planets are. This is both an intellectual exercise and predictive work: we examine the possibility that the day and night sides of the tidally locked extrasolar planets have different enough temperatures that one could observationally detect these planets as their thermal emissions vary throughout the planets' orbits. We find that, in general, the timescale for equalizing an entire planet's surface temperature is much less than the lifetime of the planet. Thus, thermally-driven surface features on any of these planets should be uniform across its surface, despite the fact that one side of the planet is constantly heated by the sun and one side of the planet is never heated directly by its star. Surface temperatures are controlled by day side albedos.

The approach that we take in this problem is to identify and characterize the different sources of heat for a rocky extrasolar planet which is close to its star. We consider insolation, heat flux due to primordial heat of accretion, and radioactivity as sources of heat. Primordial heat is the release of gravitational potential due to a planet's accretion. We also consider the relative efficiencies of conductive and convective heat transfer.

A caveat to this work is that the likelihood of a rocky giant planet existing is small. There is not enough rocky mass close to a star, for a protoplanetary disk of reasonable mass, to form a rocky planet *in situ* in a close orbit (Canup & Esposito 1996; for a nominal protoplanetary disk, the mass of a planet forming at 0.05 AU is about 0.005 M_J). It is has been suggested (e.g., Lin et al. 1996; Ward 1997; Trilling et al. 1998) that giant planets can migrate from their formation distances, presumably at the ice line (3 - 5 AU). However, giant planets forming at the ice line typically are expected to accumulate large gaseous atmospheres during runaway accretion. A mechanism for forming a Jupiter-mass (1 M_J = 318 $M_\oplus$ = 2×10^{30} g) rocky planet is not known. Nevertheless, examining the behavior of such a planet is interesting, and may at some point become relevant in planetary science. For example, rocky remnant cores of stripped giant planets may exist in close proximity to central stars (Trilling et al. 1998), and have surface and interiors relevant to the present discussion. For the sake of this model, we assume a rocky planet with a mass of 1 M_J (although the masses of the detected extrasolar planets may be as little as 0.5 M_J and as much as 10 M_J or more). The planetary radius would be around one-third Jupiter's current radius (Guillot et al. 1996). We also assume no atmosphere for these giant planets.

Extrasolar planets which are close to their central stars are tidally locked (Guillot et al. 1996). This creates a situation in which one side of the planet receives continuous sunshine, and the other is in permanent darkness. The direct radiative equilibrium temperature for a planet at 0.05 AU (51 Peg b, for example) is 1760 K; there is no direct solar heating of the dark side. There is, however, heat flow to the dark side, from internal heating. Internal heat is transported to the surface by convection. The vigor of the convection is given by the Rayleigh number, which goes as the cube of the size of the convection cell (b). In a rocky giant planet, a convection cell might easily be 10^9 cm or more, so that the Rayleigh number will be correspondingly huge. We find that the Rayleigh number for rocky extrasolar giant planet mantles is $\sim 10^{24}$, indicating that convection is extraordinarily vigorous. The Nusselt number, which is the ratio of heat convected to heat conducted, is approximately 10^7 to 10^8 for these cases, indicating that convection completely dominates transport of primordial heat. Using terrestrial values for H, the radiogenic heat produced per unit mass, we find that radiogenic heating is small, providing a heat source which is a factor 10^5 smaller than primordial heat from accretion of the planet. We find that the primordial heat flux is about a factor of twenty smaller than the solar influx. Therefore, the unequilibrated temperature for the day side is dominated by solar flux. For Jupiter, the ratio of primordial heat flux to insolation is 0.67, as opposed to 0.05 for 51 Peg b.

One goal of this work is to characterize the surface temperature of extrasolar giant planets. Among the three effects considered – insolation, primordial heat flux, and radiogenic heat flux – insolation is by far the most important. The surface temperature, without equilibration, on the day side is about 1776 K (the sum of fluxes due to insolation and primordial heating), whereas the night side temperature, without equilibration, is 815 K (no insolation – primordial heat loss only). Clearly, there is a temperature gradient between day side and night side, and heat will flow to reduce this temperature gradient. How fast does this happen? The answer to this question will resolve whether, after several billion years, a day-night side asymmetry still exists.

The characteristic velocity for convection is quite high, ~ 300 cm/sec, for vertical convection (from the interior of the planet to the surface). Horizontal convection, from the day side to the night side, spans a smaller temperature gradient, and therefore has a smaller velocity, of about 150 cm/sec. The estimates of Pekeris (1935) for zonal velocities argue for maximum velocities about a factor of 10 less than estimated above. Regardless, for characteristic lengths of $\sim 10^9$ cm, the timescale for overturn is on the order of a few years. Therefore, heat is transferred from the interior to the surface of the planet quite rapidly; and heat is transferred from the day side to the night side of the planet quite rapidly. Surface temperatures all over the planet are quickly equilibrated, due to convection, despite the fact that only one side of the planet receives direct sunlight. Any temperature gradients will be quickly erased by fast zonal convection.

From conservation of energy, therefore, the planet must radiate in all directions at a characteristic temperature, despite receiving its heat from only one direction. The incoming heat flux is absorbed over area πR_p^2, but this energy must now be radiated out over area $4\pi R_p^2$, giving an outward flux which corresponds to a radiative temperature of 1243 K, assuming that the energy is distributed evenly over the entire surface of the planet. This value is in close agreement with Guillot et al. (1996), who assumed a gaseous giant planet with instantaneous heat transfer. In fact, a rocky planet has instantaneous heat transfer as well, when considered on geologic timescales.

Because the surface temperature is so high, little topography would be expected on the planets. Topography would relax rapidly, on a timescale proportional to the dynamic viscosity of the surface. As the temperature increases, the viscosity of rocks decreases. For a hypothesized mountain chain (e.g., a crater rim) therefore, the relaxation timescale is extremely short. Very little topography is expected on superheated giant rocky planets without a separate mechanism to support the topography.

The analog in our solar system for the planets we have considered here is Venus. Venus is large enough (nearly the size of the Earth) to have a convecting mantle, and has a fairly high and uniform surface temperature. In the case of Venus, the uniform surface temperature is also aided by the presence of a massive atmosphere which rotates rapidly relative to the planet's rotation. The surface temperature, $\sim$750 K, implies that surface topography would not survive very long. Nevertheless, substantial surficial features were observed on Venus by the Magellen spacecraft (e.g., Solomon et al. 1992), implying that some process other than thermal relaxation must control the topography of Venus. This additional support could potentially be relevant on rocky extrasolar giant planets as well.

Dynamic topography, or topography supported by convection within the planet, is another possibility for rocky extrasolar planets because the convection velocities are so high. For convection velocities of a few meters per second, topography of around 10 centimeters can be supported by upward convection velocities. Since the lithospheric (thermal boundary layer) thickness is given by the convective cell thickness over the Nusselt number, and is therefore 10 - 100 centimeters for a superheated rocky extrasolar planets, we find that dynamic surface topography on the scale of the thermal lithosphere could be supported by the rigorously convecting mantle. Topography supported by convection would likely be temporary and might more closely resemble surface "waves" than fixed topography.

In conclusion, we find that for rocky extrasolar giant planets, insolation would dominate the surface temperature of the close companion planets, and surface temperatures of the tidally locked planets rapidly equilibrate through mantle convection, day to night sides. The day and night sides have the same surface temperatures, and that temperature is entirely determined by the albedo of the sunlit side. For a completely absorbing day side, the surface equilibrium temperature of a planet at 0.05 AU is 1243 K. The surfaces should be relatively free of distinguishing topography, regardless of orientation with respect to the central stars. However, convection may dynamically support small scale topography on the scale of the thermal lithospheric thickness. Albedos of extrasolar planets could be constrained by identifying the peak of black body emission from rocky planets.

References: Butler, R. P., & Marcy, G. W. 1996, ApJL, 464, L153. Butler, R. P. et al. 1997, ApJL, 474, L115. Cochran, W. D. et al. 1997, ApJ, 483, 457. Canup, R. M. & Esposito, L. W. 1996, Icarus, 119, 427. Guillot, T. et al. 1996, ApJL, 459, L35. Lin, D. N. C. et al. 1996, Nature, 380, 606. Marcy, G. W., & Butler, R. P. 1996, ApJL, 464, L147. Mayor, M., & Queloz, D. 1995, Nature, 378, 355. Noyes, R. W. et al. 1997, ApJL, 483, L111. Pekeris, C. L. 1935, Mon. Not. RAS, Geophys. Suppl., 3, 343. Solomon, S. C. et al. 1992, JGR, 97, E8, 13199. Trilling, D. E. et al. 1998, ApJ, submitted. Ward, W. R. 1997, Icarus, 126, 261. This work is supported in part by an NSF Graduate Research Fellowship.