**A SIMPLE PRESCRIPTION FOR CALCULATING DAY-NIGHT TEMPERATURE CONTRASTS ON SYNCHRONOUSLY ROTATING PLANETS.** J.I. Lunine and R.D. Lorenz, Lunar and Planetary Laboratory, 1629 E University Blvd, Tucson AZ 85721, jlunine@lpl.arizona.edu, rlorenz@lpl.arizona.edu.

**Introduction:** Although there are no synchronously rotating planets in our solar system, many of the planets indirectly detected around other stars are so close to their parent stars that they are sure to be tidally locked [1]. The day-to-night temperature contrasts on these bodies have potential implications for their evolution and spectral appearance. Both the rotation period and the thermal forcing are far removed from the parameter regimes for which conventional Global Circulation Models (GCMs) are optimized. Showman and Guillot [2] have modified a GCM to predict the day-night contrasts on extra-solar giant planets detected by radial velocity studies (assuming the physical masses of these objects are comparable to the inferred minimum masses). Such models can provide substantial physical insight because an arbitrary number of effects can be included, limited by computational capability. However, many aspects of the atmospheres of extra-solar planets are poorly known, limiting the utility of GCM's. Also, it is of interest to modelers of the evolution and physical appearance of such objects to have an economical protocol for computing day-night contrasts for inclusion in large computer codes that would be slowed excessively by computationally-intensive GCM prescriptions. We present a simple protocol here, and show that it is consistent with the results of the GCM modeling [2].

**Model:** To predict the day-night contrasts we demand energy balance and thereby construct a heat transfer coefficient determined by a general principle of Maximum Entropy Production, which has met with some success in predicting planetary climates with a minimum of prior assumptions [3].

Planetary climates may be viewed as heat engines. The system is held away from equilibrium (which is a state of maximum entropy production) by the continuous and uneven supply of solar heat, some of which (F) flows across the surface from the warm to the cool regions. Although meteorologists have developed physically sound theories for a number of individual flow mechanisms and reasonable parameterizations for their heat transport on Earth, there is there is no 'first principles' way of deducing F for a given planetary setting. This is because of the complexity of the many processes involved (latent and sensible heat transport by meridional circulation and by eddies, and the thermohaline circulation in the oceans). However, a remarkably simple principle [4], which states that convective or advective heat flows will be organized so as to maximize the rate of production of entropy, seems to correctly predict the climate state.

MEP methods have yet to be applied to giant planets, since there are two heat inputs (internal heat as well as stellar heating) to resolve. However, a simplification arises for those close-orbiting giant planets which have such high stellar irradiations that internal heat flux may be ignored. The nightside temperatures are of interest from the observational point of view, now that high time resolution transit studies can be realized. Also, some close-in giants may have radii that are actually not in equilibrium with respect to the balance of irradiation and internal heat [5]. The one GCM study of day-night temperature contrasts on such objects indicates that differences of hundreds of degrees Kelvin are possible [2].

It may be noted from energy balance that the effective temperature $T_e$ of the planet (expressed in the conventional way as $4\sigma T_e^4=I(1-A)$ where I is the solar constant, σ the Stefan-Boltzmann constant $5.67\times10^{-8}$ $Wm^{-2}K^{-4}$ and A the bond albedo) may be related to the day and nightside *effective* temperatures $T_{de}$, $T_{ne}$ as $2T_e^4=T_{ne}^4+T_{de}^4$. Assume the blackbody emission spectra from the day and nightside are sufficiently similar to allow the simplification that the infrared optical depths $\tau_{day}$, $\tau_{night}$ of the atmosphere are the same ($\equiv\tau$) for day and nightside. It then follows from the grey approximation that the day and night *surface* temperatures $T_d$, $T_n$ are given by $2T_e^4(1+0.75\tau)=T_n^4+T_d^4$. The power law index of "4" means that for a given increment in heat transport from day to night, the reduction in $T_d$ is proportionately much smaller than the increase in $T_n$, or in other words, the nightside temperature is more sensitive to heat transport than the dayside.

A reasonable simplification, one used to satisfy energy balance in a previous study [3], is that the heat transport be linearly related to the temperature contrast. That is, $F=D(T_d-T_n)$, with D a heat transport parameter. This is equivalent to the parameter used in zonal energy balance models, sometimes called a coefficient of heat diffusion, since there $F=D(dT/dx)$, where x is the sine of latitude. Considering the zonal climate to be simplified into a polar and an equatorial zone [3], $\Delta x=0.5$, thus $F=2D\Delta T$. In the present work, where the zones are two separate hemispheres, $\Delta x=1.0$ and thus $F=D\Delta T$. In zonal models for the earth, this parameter is chosen empirically to reproduce the present-day state of the climate and is of the order of 0.6 $Wm^{-2}K^{-1}$. It can also be determined from MEP considerations [3,6].

**Results:** The value of D is determined by trial and error using the condition that the rate of entropy production be a maximum. Note that these D values are lower than the results of a simple linearized model [3], because of the extreme insolation contrast in the case considered here. If B is the temperature derivative of the outgoing thermal infrared radiation, $4\sigma T^3/(1+0.75\tau)$, with T a typical temperature, the linearized model with the geometry assumed here would give $D_{mep}$=B/2. However, this approximation is derived from the assumption that stellar irradiation (and therefore planetary temperature) contrasts are modest. In such cases, the choice of 'typical' temperature is obvious. Where the stellar irradiation contrast is extreme, as here, the MEP value of D is in fact approximately equal to half of this expression, i.e. $D_{mep}$=B/4.

It is easy to generalize the prediction of temperature contrasts for extrasolar planets using MEP, both to provide useful comparisons with the GCM experiments and as stand-alone predictions. In particular, re-expressing the simple temperature contrast estimate [3] for day-night contrasts (noting that the relation of F to D has changed by a factor of 2) we have $\Delta T=I/(2D+B)$. With D~B/4, we find $\Delta T=2I/3B$. If we take the extreme of evaluating this expression at $\tau$=0, then this reduces simply to $\Delta T=4\sigma T_{eff}^4/12\sigma T_{eff}^3$, or $T_{eff}/3$. Table 1 gives the results for a number of representative close-in giant planets orbiting F- and G-dwarf stars, as well as one planet (Gl876 b) orbiting around an M dwarf. For two of these planets, depending upon the uncertain system age and minimum planet mass, internal heat from the virialized potential energy of initial collapse may compete with stellar irradiation in determining the effective temperature. For those objects the derived temperature contrast is an upper limit. (For all planets listed except HD209458b, the mass is poorly constrained since radial velocity yields only a minimum mass, which is assumed here.)

Table 1. MEP Day-night Temperature Contrasts

| Object | $T_{eff}$†(K) | $T_{day}$†(K) | $\Delta T(\tau=0)$ (K) |
|---|---|---|---|
| 70 Vir b | 380 | 427 | 126 |
| HD114762b* | 510 | 573 | 168 |
| HD 168443b* | 620 | 697 | 207 |
| Gl 876b 0.2 | 190 | 213 | 63 |
| HD209458b# | 1200 | 1350 | 400 |
| HD209458b# | 1600 | 1800 | 533 |
| HD 187123b | 1460 | 1642 | 482 |

† Input parameters ($T_{eff}$, $T_{day}$) from [7].
* For the system age, planet mass and semi-major axis of these objects, internal heat flow is likely to be significant and will reduce the day-night contrast, as well as alter $D_{mep}$, from the values given here.
# For this companion two effective temperatures corresponding to albedos of 0.5 and 0.0 are assumed [5].

At deeper levels in the atmosphere, $\Delta T$ rises modestly with $\tau$. For example, at $\tau$=1,.$\Delta T$ is 7/6 the value at $\tau$=0. Thus the basic result, namely that temperature contrasts of several hundred K are obtained on bodies with effective temperatures of 1000K, is robust and fully consistent with the preliminary GCM model runs reported by Showman and Guillot [2]. In effect, the MEP prescription selects a reasonable value of D. We therefore suggest that this model is a useful way to quickly predict day-night temperature contrasts for extra-solar planets of varying mass, age and stellar irradiation so long as the last dominates over heat flow from deep internal sources.

**References:** [1] Lin D.N.C. et al. (2000) in *Protostars and Planets IV* 1111-1134. [2] Showman A.P. and Guillot T. (2000) *B.A.A.S.., 32,* A1051. [3] Lorenz R.D., Lunine J.I., McKay C.P. and Withers P.D. (2001) *GRL, 28*, 415-418. [4] Paltridge G.W. (1975) *QJRMS, 101*, 475-484. [5] Burrows A. et al. (2000) *Ap.J., 534*, L97-100. [6] Wyant P.H., Mongroo A., and Hameed S. (1988), *JAS, 45,* 189-193. [7] Sudarsky D., Burrows A., and Pinto, P. (2001), *Ap.J., 538*, 885-903.