N87-17604

THERMAL BALANCE OF THE ATMOSPHERES OF JUPITER AND URANUS

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Two-dimensional, radiative-convective-dynamical models of the visible atmospheres of Jupiter and Uranus are presented. Zonally-averaged temperatures and heat fluxes are calculated numerically as functions of pressure and latitude. In addition to radiative heat fluxes, the dynamical heat flux due to large-scale baroclinic eddies is included and is parametrized using a mixing length theory which gives heat fluxes similar to those of Stone (1972, J. Atmos. Sci., *29, 405-418). The results for Jupiter indicate that the internal heat flow is non-uniform in latitude and nearly balances the net radiative flux leaving the atmosphere. The thermal emission is found to be uniform in latitude in agreement with Pioneer and Voyager observations. Baroclinic eddies are calculated to transport only a small amount of the meridional heat flow necessary to account for the uniformity of thermal emission with latitude. Therefore, we find that the bulk of the meridional heat transfer occurs very deep in the unstable interior of Jupiter as originally proposed by Ingersoll and Porco (1978,* Icarus *35, 27-43). The relative importance of baroclinic eddies vs. internal heat flow in the thermal balance of Uranus depends on the ratio of emitted thermal power to absorbed solar power. The thermal balance of Uranus is compared to that of Jupiter for different values of this ratio.*

I'd like to tell you about a two-dimensional radiative-convective-dynamical model that calculates the thermal balance in the visible atmospheres of the Jovian planets. It does this by calculating the zonally averaged equilibrium temperatures and heat fluxes on a pressure/latitude grid. Also, it calculates the internal heat flux entering the bottom of the model as a function of latitude. The goal of these calculations is to determine the role of meridional heat transport by baroclinic eddies versus non-uniform internal heat flow in the thermal balance of the planet, and how their roles change when we vary various external parameters that characterize the planet such as the radiative time constant, internal heat source, planetary radius or whatever is an important parameter. First I'll describe the model and how the model calculations are done and then I'll tell you about some preliminary results for Jupiter and Uranus.

In applying the model we have to adopt certain simplifying assumptions. The most important of these is that we assume that the deep atmosphere is convective so that all fluid elements in the convective interior are on the same adiabat. This assumption is supported by the work of Ingersoll and Porco (1978) for Jupiter, and we assume it to work for Uranus as well. We also assume that the dynamical heat flow in stable areas is due to large-scale baroclinic eddies. Other assumptions that we make in the model are that the opacity is due to H_2 alone, the specific heat is independent of temperature, the albedo is constant with latitude and we ignore seasonal variations and latent heat effects.

I'll show you a list of the heat fluxes that we include in the model. The infrared radiances are calculated using the two-stream approximation. Solar fluxes are fit to other people's work such as Hunten, Tomasko and Wallace (1980) for Jupiter, and Wallace (1980) for Uranus. The dyanamical heat fluxes are calculated wherever the stratification is stable. We used a mixing length formulation that was developed by Ingersoll and Porco (1978) in their *Icarus* paper. In the limit of strong stable stratification, their formulation gives the same expression for heat fluxes in terms of local potential temperature gradients as the work of Stone (1972) in his radiative-dynamic model.

We do a convective adjustment wherever the stratification is unstable. What we do is we adjust the temperature profile back to an adiabat while conserving the enthalpy of the layer. An exception occurs when the unstable layer is in contact with the deep convective interior. In that case, we assume that that layer can extract the heat necessary from the deep convective interior to maintain it on the deep adiabat.

Figure 1 is a plot of fluxes versus latitude for Jupiter, for a ratio of the power emitted from the planet to the absorbed solar power of E = 1.6. The fluxes are expressed in units of the effective temperature of the planet which we used as 125.4 K. You can see that the internal heat flux is non-uniform in latitude, which is an interesting feature that I will try to explain.

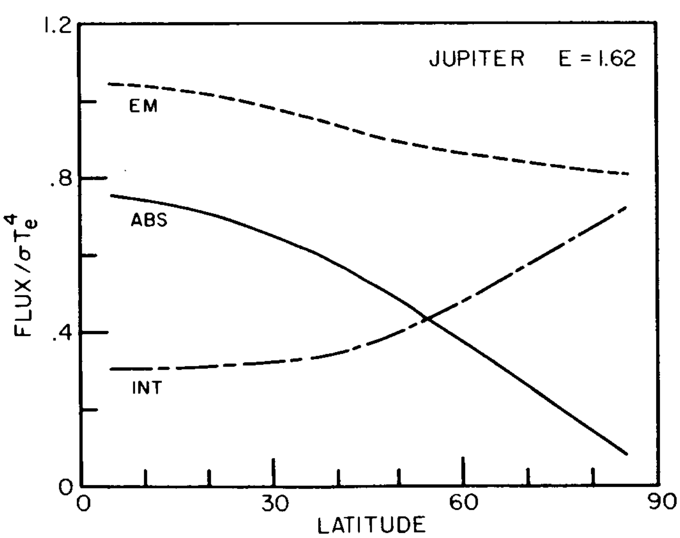

Figure 1. Flux vs. latitude for Jupiter. Ratio of total emitted power to absorbed sunlight is E=1.62. EM is emitted thermal flux, ABS is the absorbed solar flux, and INT is the internal flux. The fluxes are expressed in units of 14 W m^{-2}.

The first thing that you notice about the results for Jupiter is that the dynamical heat flux plays a small, or nearly negligible role on the thermal balance. This is not too surprising since Stone's radiative-dynamical model basically predicted this for Jupiter. The consequence of this is that Jupiter is close to radiative-convective equilibrium at every latitude and therefore, just to conserve energy, the internal heat flux must balance the net emission to space (i.e., IR minus solar radiated flux) to conserve energy. To understand why the internal heat flux is non-uniform in latitude, we can ask an equivalent question, which is why the thermal emission is relativiely uniform. The answer to this is that it's related to the fact that we have taken the adiabat at depth to be uniform with latitude. To see why this would make any difference, one can do the following calculation: you fix the adiabat at depth and work out the grey radiative-convective equilibrium of a column of gas, assuming the solar deposition is all very deep in the convective region. The answer you get is that the thermal emission has to be constant in latitude. The emission in Fig. 1 isn't exactly constant in latitude, but that is because the solar heating has not been all deposited deep in the convecting region in this particular model.

Near the equator, the solar heating stabilizes the atmosphere at a greater depth relative to the poles, producing a 4.4 K difference in the effective temperature from the equator down to 50 deg latitude. The analysis by Pirraglia on Voyager 1 IRIS data indicates that this difference is unlikely to be greater than about 3.5 K.

Figure 2 is a flux versus latitude plot for Uranus, where the fluxes are annual averages. We see that the major difference between this and Jupiter is that we have a uniform internal heat flow when the ratio of emitted to absorbed power is 1.16. Stone has argued that Uranus' long radiative time constant and negligible internal heat source should cause dynamics to be highly stabilizing in the atmosphere. Large-scale eddies, in that case, should be very efficient in transporting heat from the hot pole to the cooler equator. This is basically what we are finding in our model. We are finding that the meridional flux due to large-scale eddies is very efficient and therefore the internal heat flow doesn't have to do any of the meridional heat transport. That is basically the behavior that we find for all ratios of emitted to absorbed power of 1.25 or less.

Now I'll show you a case where basically I jacked up the potential temperature of the interior. In other words I made it hotter in the center so that the internal heat flux is higher. You see in Fig. 3 that the emitted-to-absorbed power here is now 1.5. You get 0.5 K effective temperature difference from equator to pole for the emission, but now you see that the internal heat flow wants to come up and balance the difference in emitted minus absorbed flux towards the equator.

This seems to be a state intermediate between a low-E Uranus and a high-E Jupiter case. So we can at this stage imagine a suite of hypothetical Jovian planets ranging from the low-E Uranus, where large-scale eddy motions dominate, to the high-E Jupiter case, where the internal heat dominates. As the internal heat source becomes larger, the atmosphere becomes more unstable, but the opportunity arises for differential flow of the internal heat to reduce

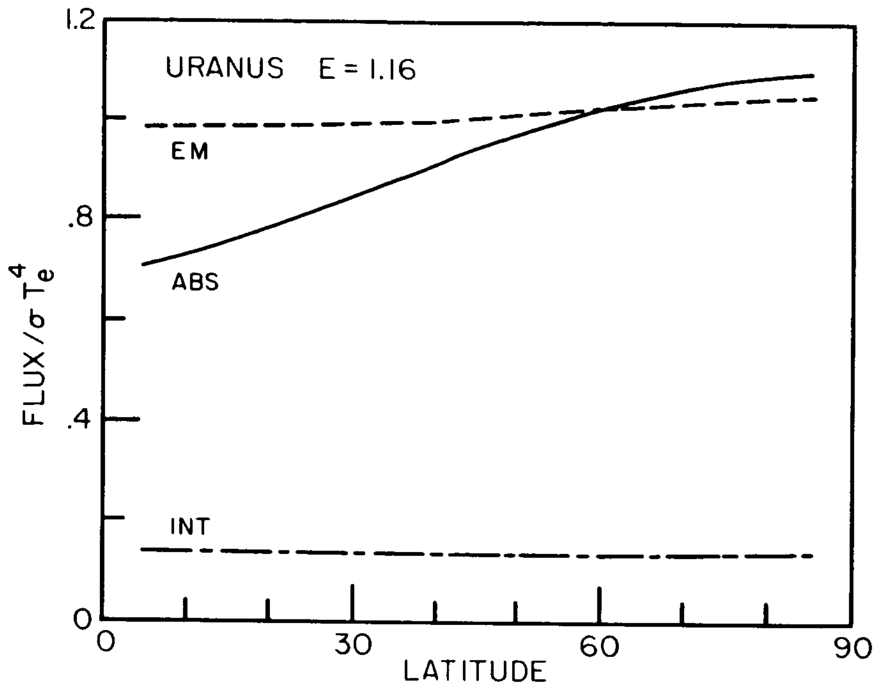

Figure 2. Flux vs. latitude for Uranus. Unit of flux is 0.66 W m^{-2}. The solid curve is the annually-averaged absorbed solar flux.

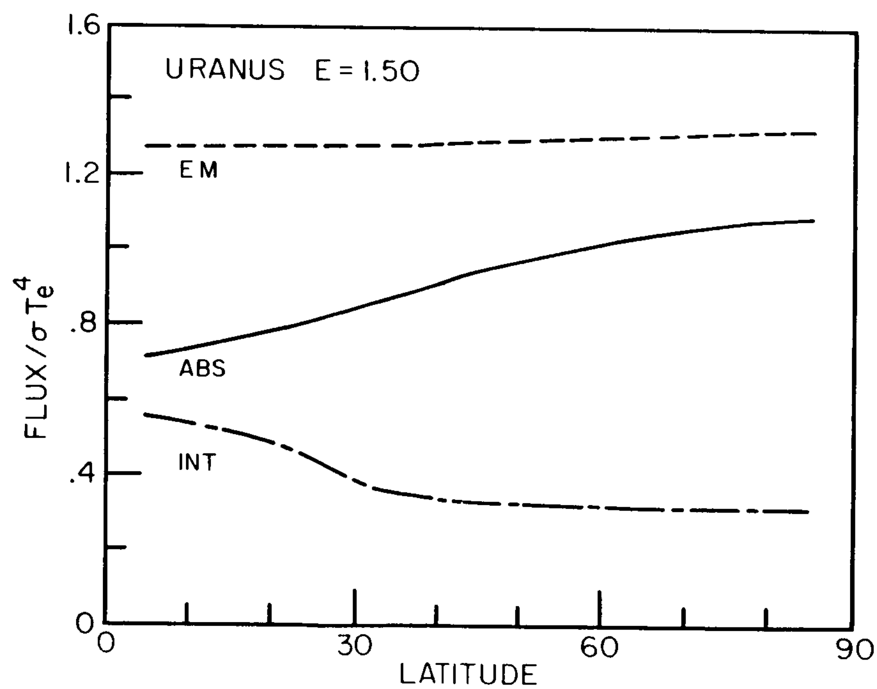

Figure 3. Same as Fig. 2 except here E=1.50.

the effect of temperature difference from the equator to the pole. This is all fine provided that the solar flux is deposited relatively deep in the convective region. If it's shallow then you can get a different result. Should the solar heating occur deep relative to the radiative convective boundary on all the Jovian planets, then we expect that thermal emissions should be fairly uniform in latitude for all these planets. Thank you.

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DR. STONE: I am not too clear on how the model is constructed. In particular, the heating varies latitudinally. You have a different solar input at different latitudes based on observed albedos, I presume. Then you said that that is being put in fairly deep, so you are calculating the structure at highter levels?

DR. FRIEDSON: Well, I took the solar flux curves for Jupiter from the paper by Hunten, Tomasko and Wallace (1980). I have parametrized the solar input and I have not played too much with that.

DR. HUNTEN: A third of the solar radiation is absorbed above the radiative convective boundary.

DR. STONE: All right, that is put in your model, then, but what did you assume about the heat input at the lower boundary?

DR. FRIEDSON: As you go deep into the atmosphere, our assumption is that you get into a convective region which can maintain all the temperatures as a function of latitude on the same adiabat. Your boundary condition is that your temperature profile, no matter at what latitude, has to approach the same adiabat.

DR. ORTON: For the Jovian models, where is the radiative-convective boundary located, and does that vary with latitude?

DR. FRIEDSON: It varies with latitude generally, but in this particular model the radiative-convective boundary near the pole can be as high as 600 millibars or so. Near the equator, it can be sub-adiabatic, only just slightly so, down to pressures of about one bar.

DR. KAHN: Is there any hope of using the time dependent data and doing a time dependent model here between the limbs and so on? Can we constrain the cloud structure a little bit better that way?

DR. FRIEDSON: I think it is possible that if you really believe our parametrization for horizontal fluxes, which is really just a mixing length theory, you take that as strictly true, and you ignore any horizontal fluxes, then you can possibly use this model to try to probe what the solar flux is doing, what scattering there is and so on, because you have to fit the uniform emission. Right now our model is a bit crude for that, and I think it would need a lot of refinement before I tried anything like that.

DR. BAINES: Because of methane absorption of solar energy, you find that a large part of that solar energy is being deposited around 500-700 millibars for Uranus. The calculations I did around a year or two ago show that you can get a degree difference in the space of ten years. That is not much, but Uranus has a very low effective temperature. It seems that the winds generated may be a function of pole orientation.

DR. HUBBARD: Do your models include a variation of gravity from equator to pole? That can make a difference on the order of the differences in temperature that you are calculating for the equator.

DR. FRIEDSON: No. I hold gravity constant in latitude. Are you saying that it makes a large difference in the effect of column mass abundance?

DR. HUBBARD: Due to the adiabat that you are on to some extent...

DR. FRIEDSON: Well, if it is only changing the adiabat, I have ignored the temperature dependence of the specific heat or whether it is affected by the ortho-para hydrogen ratio. So, you know, the actual model for Uranus right now is rather crude in terms of getting the vertical profiles right. I think qualitatively the behavior will not change much once it is refined.

DR. POLLACK: How do you calculate the meridional dynamical heat fluxes?

DR. FRIEDSON: We use a parametrization that is in terms of local potential temperature gradients. Basically, it is rather complicated to describe, but it is based on a mixing length analysis, and you can find out exactly what the formulae for the fluxes are from Ingersoll and Porco (1978). Usually in our model where we do get significant dynamical heat fluxes, stratification is very stable. In that case we actually have the same parametrization as Stone's (1972) radiative dynamical heat fluxes.

DR. STONE: In those calculations I did in 1972, I neglected beta effects. Things that have been done since then now give us a pretty good idea of whether the beta effects would be important and how to take them into account. I never myself tried to make any estimate of whether they would be important on Uranus, where you are finding the more stable states. Have you made any estimates of whether beta effects might be important?

DR. FRIEDSON: No. I haven't looked at that, actually.

DR. HUNTEN: What are beta effects?

DR. STONE: Beta is the variation of Coriolis parameter with latitude, which can have strong stabilizing effects on the dynamics.

DR. SROMOVSKY: I'm curious about the time constant for the effect in which the internal heat flux tends to balance the solar deposition. Is that time constant so long that it would inhibit a response to asymmetries in the solar deposition?

DR. FRIEDSON: Well, actually, in the convective envelope, just below say around the 5 bar level and below, you have very short time scales for the convection and the flux can change on the order of hours to maybe a day where it is convectively unstable. If I really believed that we could get a lot of seasonal data on Uranus to watch how the emission changes over the season, then it might be possible to look for the difference in phase response for areas which would be dynamically dominated by the eddies versus areas that are dominated by the internal heat flux.

DR. STONE: In the case of Uranus did you take the average of the whole orbit?

DR. FRIEDSON: Yes, it is annually averaged.

DR. STONE: Because I remember that the mean equator-to-pole temperature difference is relatively small compared to what you could get at the seasonal extreme.

DR. FRIEDSON: Our globally averaged temperature difference for Uranus is very small, and I believe that Wallace's (1983) amplitudes were about 2.5 K, and we just have an annually averaged temperature difference of 1 K. So, yes, I do think you get some variation of emission with season, but I think you have to be able to follow that over a long period of time.