1. INTRODUCTION

1.1 Science background
Pluto's N₂-CH₄-CO atmosphere is compositionally similar to those of Triton and Titan. Its N₂-dominated atmosphere resembles Triton and Mars in that its atmosphere, in vapor-pressure equilibrium with its ices, varies seasonally as the frost distribution and temperature changes.

As Pluto's heliocentric distance varies from 30 to 50 AU, the incident solar flux varies by nearly a factor of three. Because the surface pressure of N₂ frost is an extremely sensitive function of frost temperature (Brown and Ziegler 1980), Pluto's surface pressure is expected to change by orders of magnitude during its year, but it is unknown how its vertical structure changes seasonally.

We propose to combine a state-of-the-art volatile-transport model (including an atmospheric planetary boundary layer) and an atmospheric radiative-transfer model in the first investigation of the thermal structure of Pluto's seasonal atmosphere. New observations, especially the 2002 occultations (Elliot et al. 2003; Sicardy et al. 2003), make this a timely area of study.

1.2 Previous models
The first generation of Pluto seasonal models identified the essential role of vapor-pressure equilibrium and volatile transport, assuming a methane-dominated surface (e.g., Trafton & Stern 1983).

During the late 1980s and early 1990s, observers made the first maps of Pluto (e.g., Young, E. F. 1993), identified the surface frosts (Owen et al. 1993), detected Pluto's atmosphere (Elliot and Young 1992), and measured Pluto's temperature (see refs. in Spencer et al. 1997) and the temperature of its N₂ frost (Tryka et al. 1994). These provided the impetus for the second generation of seasonal models (Trafton 1990; Young 1993; Hansen & Paige 1996)

that included N₂ as a dominant species and matched the surface pressures deduced from the 1988 stellar occultation. These papers drew general conclusions, such as the likelihood of a secondary maximum in pressure at the aphelion equinox, but were hampered by the difficulty of extrapolating from a single point. Furthermore, they have modeled surface pressure vs. time, but not the vertical structure of the atmosphere.

During this same time period, efforts to reproduce the thermal structure of Pluto's atmosphere (Yelle and Lunine 1989; Lellouch 1994; Strobel et al. 1996) focused on Pluto's 1988 atmosphere. Without other occultations, it was previously underconstrained to model the atmosphere at other seasons.

Since the 2002 occultations, one study has combined volatile-transport models with calculations of the vertical structure (Young 2004). This was a simplified model (global N₂ frost, optically thin atmospheric heating and cooling) that quantitatively reproduced the changes between the 1988 and 2002 occultations. A goal of this proposal is to add realistic physics to the linked volatile-transport/atmospheric structure model.

1.3 Recent advances
In 2002, two of Pluto occultations were observed, the first since 1988 (Buie et al. 2002; Elliot et al. 2003; Sicardy et al. 2003; Pasachoff et al. 2005), showing that Pluto's atmospheric pressure has doubled in the intervening 14 years. While previous seasonal models had a snapshot of Pluto's atmosphere, we now have both a value and a derivative.

Our knowledge of Pluto's surface has steadily grown, through improved instrumentation and perseverance. We now have evidence for a variety of surface types on Pluto, including CO concentrations, pure CH₄ and CH₄:N₂ solutions, H₂O, and tholins (Doute et al. 1999; Grundy & Buie 2001, 2002; Olkin et al. 2004). ISO has detected
Pluto's thermal lightcurve, from which researchers deduce temperatures, emissivities, and thermal inertia (Lellouch et al. 2000b). New thermal measurements have been made from Spitzer.

Theoretical advances include the role of a turbulent boundary layer for diffusion of heat and minor species (Stansberry et al. 1996b), and calculations of a discontinuity in the N₂ emissivity at the α-β phase transition (Stansberry & Yelle 1999).

1.3 Related work

This proposal is a renewal of a proposal of the same name, submitted in 2004 and funded for a one-year pilot study. Since the reviewers raised concerns about the availability of observational constraints, we describe our two synergistic observational programs to test the predictions of our proposed models.

The first program is a new 3-year Planetary Astronomy grant (Timing Pluto's Changing Atmosphere with Multiple Occultations) to observe Pluto stellar occultations, by far the most sensitive means of measuring Pluto's changing atmosphere. (Timing Pluto's Changing Atmosphere with Multiple Occultations, L. Young PI). Because of improved occultation systems and Pluto's crossing of the dense starfields of the Milky Way, this collaboration between SwRI, Lowell Observatory, and Wellesley College should yield three occultations over the next three years. Earlier this year, we observed a Pluto occultation from Sommers-Bausch Observatory in Boulder, CO (at best a grazing event), and will observe a Charon occultation from three telescopes in Chile in July 2005.

The second program is an ongoing NASA Planetary Astronomy proposal (Interacting Surfaces and Atmospheres of Pluto and Triton, E. Young PI) to observe Pluto and Triton with a variety of techniques. Through this program, we construct maps that can be compared with predicted albedo distributions, observe moderate resolution IR spectra that can be compared with predicted frost compositions, mixing states, layering, and temperatures, and measure atmospheric absorption with high-resolution spectra that can be compared with predicted atmospheric temperature and composition.

2. SCIENTIFIC OBJECTIVES

We propose an investigation linking a planetary boundary layer/volatile transport model with a model of atmospheric energy balance, which together will model the distribution of frosts on Pluto's surface and the thermal structure of Pluto's atmosphere as a function of season. This model will provide the intellectual framework for interpreting observations of Pluto's changing atmosphere and surface.

This model will improve our fundamental understanding of Pluto's coupled surface and atmosphere. Did Pluto's atmosphere double between 1988 and 2002 because of thermal inertia, changes in the latitudes of frost coverage, darkening of frosts, changes in illumination on a static frost, or some combination? How does the composition of the atmosphere depend on the surface's temperature, composition, and mixing state? Are the energetics of Pluto's atmosphere dominated by IR heating and cooling at some seasons, and by UV and conduction at other seasons?

With an improved understanding of Pluto's surface and atmosphere, we will be able to make near-term predictions to guide observations, including plans for the New Horizons mission to Pluto. How quickly does the frost distribution change, and will it be observable by HST? How quickly does Pluto's atmospheric composition change, and is this detectable by high-resolution spectroscopy? How does the thermal structure of Pluto's atmosphere change, and how does this affect occultation
observations? What is the range of atmospheres the New Horizons spacecraft might measure in 2014, and how will this affect spacecraft operations?

A seasonal model of Pluto's atmospheric structure addresses questions of Pluto's long-term evolution. What are the temperatures and pressures in Pluto's upper atmosphere throughout its year, and how does that relate to the long-term escape rate of the atmosphere? What is the UV opacity of the atmosphere as a function of season, and does this lead to a latitudinal dependence on the photochemical processing of the surface?

3. APPROACH AND METHODOLOGY

3.1 Project overview

We will adopt existing volatile transport and atmospheric energy-balance models to make a linked seasonal surface-atmosphere model that can predict the changing surface and atmospheric structure. This linked surface-atmosphere model will use recent observational constraints and make concrete, testable predictions about surface frosts and atmospheric structure.

![Diagram](image)

Fig. 1. The linked Planetary Boundary Layer/Volatile Transport (PBL/VLT) and Atmospheric Structure/Radiative Transfer (RT) models.

The linked model has two components (Fig. 1), Planetary Boundary Layer/Volatile Transport (PBL/VT, Section 3.2) and Atmospheric Structure/Radiative Transfer (RT, Section 3.3). The inputs to both components are listed in Table I, the connection between them is listed in Table II, and examples of model outputs that can be compared with observations are listed in Table III.

The core of the PBL/VT model will use an existing model of N2 frost transport on Triton, written and maintained by Co-I Spencer (Spencer 1990a, Spencer and Moore 1992), with the addition of a Planetary Boundary Layer (PBL) to calculate the transition to a local atmosphere and the movement of minor volatile species. The core of the RT model is based on a model used in Jupiter's thermosphere (Yelle Griffith and Young 2001; hereafter YGY).

<table>
<thead>
<tr>
<th>Table I. Model parameters (inputs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planetary Boundary Layer/Volatile Transport</td>
</tr>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Initial frost distribution</td>
</tr>
<tr>
<td>Frost, substrate albedo</td>
</tr>
<tr>
<td>Frost, substrate emissivity</td>
</tr>
<tr>
<td>Thermal inertia</td>
</tr>
<tr>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>Specific heat</td>
</tr>
<tr>
<td>N2 inventory</td>
</tr>
<tr>
<td>Drag coefficient</td>
</tr>
<tr>
<td>Roughness sublayer</td>
</tr>
<tr>
<td>Sticking coefficient</td>
</tr>
<tr>
<td>Permeability</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Atmospheric Structure/Radiative Equilibrium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Thermal conduction</td>
</tr>
<tr>
<td>CH4 line lists</td>
</tr>
<tr>
<td>V-T transition probability</td>
</tr>
<tr>
<td>CO line lists</td>
</tr>
<tr>
<td>UV heating efficiency</td>
</tr>
</tbody>
</table>

Because the timescales for the thermal balance in the atmosphere are short compared to those for the seasonal change, we can separate the PBL/VT and the RT models (Table II), greatly simplifying the model and improving computational efficiency.
Table II. PBL/VT-RT interface

<table>
<thead>
<tr>
<th>PBL/VT step</th>
<th>RT Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂ frost transport (3.2.2)</td>
<td>Surface pressure</td>
</tr>
<tr>
<td>Turbulent heat diffusion (3.2.4)</td>
<td>Height of PBL</td>
</tr>
<tr>
<td>CH₄/CO frost transport (3.2.5)</td>
<td>CH₄/CO mixing ratio</td>
</tr>
</tbody>
</table>

Table III. Model observables (outputs)

<table>
<thead>
<tr>
<th>Planetary Boundary Layer/Volatile Transport</th>
<th>Observable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model output</td>
<td></td>
</tr>
<tr>
<td>Albedo distribution</td>
<td>Photometry, maps</td>
</tr>
<tr>
<td>Frost composition, mixing state, grain size, temperature</td>
<td>Moderate-resolution near-IR spectra, phase curves</td>
</tr>
<tr>
<td>Emissivity, temperature, thermal inertia</td>
<td>Far-IR emission</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Atmospheric Structure/Radiative Equilibrium</th>
<th>Observable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model output</td>
<td></td>
</tr>
<tr>
<td>Number density structure</td>
<td>Occultation lightcurves</td>
</tr>
<tr>
<td>Composition and temperature</td>
<td>High-resolution atmospheric absorption, radio emission</td>
</tr>
</tbody>
</table>

3.2 Planetary Boundary Layer and Volatile Transport (PBL/VT)

3.2.1 Overview

The surface pressure on Pluto is controlled by vapor-pressure equilibrium with the frozen form of the atmosphere's main constituent, N₂. As long as the atmosphere is global (i.e., as long as the sublimation winds are subsonic), the surface temperature of the N₂ ice and the surface pressure of the N₂ atmosphere are the same all over Pluto; areas with high insolation lose energy through latent heat of sublimation, while areas with low insolation are condensation sites and gain latent heat (Trafton and Stern 1983). The temperature of the N₂ ice depends on its globally averaged insolation. As the N₂ ice temperature changes, the surface pressure changes to maintain vapor-pressure equilibrium. This basic model has been the paradigm for Pluto for two decades.

Previous volatile transport models have included neither the increase of sublimation winds due to their confinement to an Ekman layer (Ingersoll 1990; Spencer et al. 1997), nor the role of a turbulent surface layer on the transport of the minor species CH₄ and CO (Stansberry et al 1996b). The Ekman layer and surface layer together form the Planetary Boundary Layer.

For Pluto, the model will begin with an initial description of Pluto's surface volatile coverage (i.e., frost depth and composition vs. location), step through the Pluto year updating the surface albedo, temperature, and composition at each step, and continue iterating, typically for hundreds of Pluto years, until either Pluto's seasonal ices are reproduced from one year to the next or solution diverges, eliminating that combination of input parameters.

The basic PBL/volatile-transport model will assume longitudinal homogeneity. Later in this program, we will allow frosts to vary with both latitude and longitude for direct comparison with albedo maps.

At each time step, our model will consist of five steps:

1. Surface temperatures and N₂ frost transport. Starting with a frost distribution (e.g., composition, frost depth, albedo) and N₂ frost temperatures, calculate heating rate of N₂ frosts, temperature of frost-free areas,
surface pressure, and \( \text{N}_2 \) sublimation or condensation rates.

2. **Sublimation winds.** From the \( \text{N}_2 \) sublimation/condensation rates, calculate the Ekman depth and the sublimation wind speeds.

3. **Turbulent diffusion.** From the surface temperatures (frost and non-frost) and the Ekman depth and sublimation wind, calculate the coefficient of turbulent heat transfer and the temperature above the PBL.

4. **\( \text{CH}_4 \) and \( \text{CO} \) frost transport.** From the coefficient of turbulent heat transfer and the frost distribution and temperature, calculate the sublimation and deposition rates of \( \text{CH}_4 \) and \( \text{CO} \) frost and their atmospheric mixing ratios above the PBL.

5. **Timestep.** We can ignore effect on the frosts of the atmosphere above the PBL. From steps 1-4, we calculate the frost distribution and temperature for the next time step.

The framework is similar to Spencer (1990a) and Spencer and Moore (1992), whose volatile-transport model included \( \text{N}_2 \) transport, sublimation wind speeds, and updating the timestep.

### 3.2.2 Nitrogen frost transport

**Significance of Nitrogen frost transport:** Trafton and Stern (1983) laid out the basic physics of Pluto's volatile transport and thermal control of the atmospheric pressure, where latent heat transport maintains Pluto's \( \text{N}_2 \) frost at a single temperature across the planet, with a nearly uniform atmospheric surface pressure.

**\( \text{N}_2 \) frost temperature:** As long as Pluto's atmosphere is thick enough to transport atmospheric \( \text{N}_2 \) globally, the global balance of absorbed sunlight and emitted thermal radiation controls \( T_{\text{N}_2} \). Ignoring sensible heat content and transport within the frost layer (justified to first order in Spencer and Moore (1992)), the local energy balance for frost-covered regions can be written as

\[
k \left( \frac{\partial T}{\partial x} \right)_{x=0} + F_{\text{sun}} (1 - \alpha) + \dot{m}_{\text{N}_2} = \varepsilon \sigma T_{\text{N}_2}^4 \tag{1}
\]

where \( k \) is the substrate thermal conductivity, \( x \) is depth into the substrate, dots indicate time derivatives, \( \dot{m}_{\text{N}_2} \) is the mass-per-unit area of the frost, \( T_{\text{N}_2} \) is the \( \text{N}_2 \) frost temperature, \( F_{\text{sun}} \) is the solar flux (taking into account the diurnally averaged incidence angle and heliocentric distance), \( \alpha \) is the albedo, \( \varepsilon \) is the emissivity, \( \sigma \) is the Stefan-Boltzmann constant, and \( L \) is the latent heat of sublimation. Frost-free surface temperatures are calculated the same way, but without the latent heat term, and frost is assumed to condense on frost-free regions if they become colder than the frost temperature. Differing albedos are assumed for the frosted and frost-free regions.

At each timestep, we will use Eq. 1 to find the local mass flux of solid \( \text{N}_2 \) needed to balance energy locally. Typical mass fluxes for sample models are of order 1-2 g/cm²/year.

**Frost-free regions:** Portions of Pluto's surface free of \( \text{N}_2 \) frost will have temperatures that balance local thermal emission and diurnally averaged insolation (Spencer 1990b). Frost-free areas that are warmer than \( T_{\text{N}_2} \) can remain warm, as they have no frosts to sublime, while frost-free areas that are colder than \( T_{\text{N}_2} \) are marked as frost-covered in the next time step.

**Model parameters:** The albedo, emissivity, and thermal properties of \( \text{N}_2 \) and frost-free areas are constrained by interpretations of 60 and 100 \( \mu \text{m} \) thermal emission from Pluto (Lellouch et al. 2000b). The emissivity of \( \alpha - \) and \( \beta - \text{N}_2 \) have been modeled by Stansberry et al. (1996a). The similarity between the mutual-event maps (1985-1990; Young et al. 1999) and HST maps (1994; Stern et al. 1997) implies a minimum \( \text{N}_2 \) inventory on the frost-covered,
sunlit side of 5 g/cm², while the non-isothermal surface implies areas free of N₂ frost, which would not occur for depths of N₂ greater than 200 g/cm².

Of these parameters, the thermal inertial is the most interesting (Fig. 2), as it can delay Pluto’s atmospheric maximum for decades after perihelion (Hansen & Paige 1996, Young 2004).

3.2.3 Sublimation winds
Significance of the sublimation winds:
The flux of atmospheric N₂ from the subliming to the condensing latitudes, drives a sublimation wind. Latent heat transport can maintain a global atmosphere at Pluto with isothermal N₂ frost temperature only if the sublimation wind is less than the sound speed (Trafton and Stern 1983). Thus, the sublimation wind speed distinguishes a global atmosphere with efficient global volatile transport from a local atmosphere with limited or no volatile transport. Viscosity and Coriolis forces act to confine the sublimation winds to an Ekman layer at the base of the atmosphere (Ingersoll 1990).

A shallow Ekman layer increases the sublimation wind needed to transport a given mass. Moreover, the depth of the Ekman layer and the wind speed are related to the friction velocity, used later to estimate mass and energy fluxes.

Calculating the sublimation winds: The meridional mass flux of atmospheric N₂ through the atmosphere is related to the N₂ flux from the surface through conservation of mass. Only thick atmospheres can support global transport: a small density needs a large sublimation wind to supply the same mass flux.

Sublimation winds are most likely confined to an Ekman layer (Ingersoll 1990), which depends on latitude. In the tropics or for small densities, the Ekman layer approximation gives an Ekman depth that is greater than the scale height, an unphysical result; we follow the assumption of Spencer et al. (1997) that whole-atmosphere flow occurs when Ekman layer theory breaks down.

\[ v = \frac{\dot{M}}{\rho_0 d} \]

\[ d(\lambda) = \min \left\{ \frac{\sqrt{MC_p/\Omega \rho_0 \sin \lambda}}{H} \right\} \quad \text{(PBL)} \quad \text{(2)} \]

where \( v \) is the sublimation wind, \( \dot{M}(\lambda) \) is the meridional mass flux of atmospheric N₂ across a given latitude (g/cm/s), \( \rho_0 \) is atmospheric density at the surface (g/cm²), \( d \) is the depth of the Ekman layer (cm), \( C_p \) is the drag coefficient (unitless), \( \lambda \) is the latitude, \( \Omega \) is the planetary rotation rate (s⁻¹), and \( H \) is the atmospheric scale height (cm).

Eq. 2 will be used to test supersonic sublimation winds. When sublimation wind speeds exceed the sound speed, we will cease global transport of N₂. One very reasonable action is to simply cease frost transport at this time, until the wind speeds once again become subsonic. As part of the proposed work, we will investigate more
sophisticated ways to incorporate transport during a non-global atmosphere.

**Model parameters:** The only unspecified parameter for the sublimation wind speeds is the drag coefficient. Ingersoll (1990) found a good match to Triton wind streaks with a nominal value of 0.002, for which the atmosphere becomes local near a pressure of 0.1 µbar, and a surface temperature of 31.0 K. Through Eq. (2), \( \nu \) is inversely proportional to \( \sqrt{C_D \rho_0} \), so a small value of \( C_D \) hastens transition from a global to local atmosphere (for \( C_D = 0.0002 \), the transition occurs near 1 µbar, 33.7 K). Thus, this parameter is most important in this step for models with low frost temperatures and small drag coefficients. For many of our models, we expect to be insensitive to \( C_D \).

### 3.2.4 Turbulent diffusion of heat to the atmosphere

**Significance of convective heat flux:** Pluto's surface temperatures span a large range, with cold areas near ~38 or 40 K and warmer areas near ~60 K (Tryka et al. 1994; Lellouch et al. 2000b). If the base of the atmosphere is near the average surface temperature (Stansberry et al. 1992), then the atmosphere will be warmed or cooled by contact with the warm or cool surface. Heating by direct conduction is small; for thermal gradients of ~10 K/km suggested by the 1988 occultation (Yelle and Elliot 1997), the heat flux into Pluto's surface from the atmosphere is ~0.04 erg/cm²/s.

A potentially larger source of heat transfer between the surface and atmosphere is the turbulent diffusion of heat through a planetary boundary layer (Stull 1988; Garratt et al. 1992; Stansberry et al. 1992). On Triton, the turbulent heat flux is significant, ~5 erg/cm²/s for upward heat flux and ~0.3 erg/cm²/s for downward (Stansberry et al. 1992).

This is a negligible fraction of the solar flux absorbed by Pluto's surface. The significance for this project lies in describing the properties of the turbulent layer, which will then be applied to the transport of CO and CH₄.

**Calculating turbulent heat flux:** Following Stansberry et al. (1992), we assume global balance of turbulent heat flux, which implies that the atmospheric temperature, \( T_A \), above the surface layer equals a global average of the surface temperatures, \( T_s \), weighted by the efficiency of heat flux over cold, frosted and hot, unfrosted areas.

The heat flux to the surface, \( F \) (positive for downward flux), is positive if the atmosphere is warmer than the surface (Stansberry et al. 1992; Garratt 1992):

\[
F = \rho v u_c C_H (T_A - T_s)
\]

(3)

The friction velocity, \( u_* \), is derived from the sublimation wind speed, \( v \), and the drag coefficient, \( C_D \) (Ingersoll 1990):

\[
u_* = v \sqrt{C_D}
\]

(4)

The heat transfer coefficient is a more complex function that depends only on two parameters: the Monin-Obukhov stability length, \( L_{MO} \), and the depth of the roughness sublayer (Fig. 2). \( L_{MO} \) in turn depends on the heat flux, \( F \), as well as known quantities such as friction velocity and atmospheric density at the surface. Eq. 3 is an equation with one unknown, \( F \), which appears explicitly on the left hand side, and through \( C_H \) on the right. Once Eq. 5 is solved for \( F \), the parameters \( L_{MO} \) and \( C_H \) can be calculated and used for CH₄ and CO fluxes.

**Model parameters:** The only new parameter needed for this step is the depth of the roughness sublayer. While this parameter is very poorly constrained, it has only a small effect on the heat transfer coefficient; CH over hot areas is essentially constant, and \( C_H \) over cold areas varies by an order of magnitude, with the effect of only changing the atmospheric temperature above the sublayer by a few degrees (Stansberry et al. 1992).
3.2.5 Methane and carbon monoxide frost transport

Significance of CH₄ and CO: Of the three volatiles seen on Pluto's surface, N₂, CO, and CH₄, N₂ has the largest vapor pressure and is expected to dominate the atmospheric composition. This expectation is supported by a detection of gaseous CH₄ at roughly 1% (Young et al. 1997) and upper limits on atmospheric CO (Young et al. 2001, Bockelée-Morvan et al. 2001).

Although Pluto's atmosphere is primarily N₂, CH₄ and CO control the radiative heating and cooling in the atmosphere. The minor species therefore control the atmospheric temperatures and, ultimately, the escape rates. In the UV, both N₂ and CO are transparent to Lyman-α at 1216 Å. Not only does this make CH₄ important for UV heating, it also means CH₄, not N₂, shields the surface from Lyman-α. Thus, both surface and gas-phase photochemistry depend on how the CO and CH₄ column varies with season.

While CO and N₂ frosts are completely miscible, CH₄ and N₂ are not (Prokhvatilov & Yantsevich 1983). A mixture of CH₄ and N₂ will separate into nearly pure N₂ (with a maximum of ~4% CH₄) and nearly pure CH₄ (with a maximum of ~3% N₂). This separation may happen during the deposition phase for an atmosphere with abundant CH₄, and is expected to occur during the sublimation phase, when the more volatile N₂ preferentially sublimes, leaving behind the less volatile CH₄ frost as a "lag deposit." Observations support this picture; on Pluto (unlike Triton), nearly pure CH₄ frost has been detected spectroscopically (Doute et al. 1999).

Despite their importance, little work has been done on modeling the seasonal variation of atmospheric CH₄ and CO. In the only published study of the seasonal variation of atmospheric CH₄ on Pluto, an idealized, 1-D model (Trafton 1990) predicts that the CH₄ mixing ratio is a thousand times smaller at aphelion than perihelion, if the volatile reservoir is less than 30% CH₄. In contrast, other idealized models (such as intimate mixtures where the mixing ratio of the ices stays constant with season) will have a higher CH₄ mixing ratio at aphelion than perihelion.

CH₄/CO mass fluxes and atmospheric abundance: The vertical mass flux of the minor species balances when averaged over the planet (Stansberry et al. 1996b), following the same argument as for the mass balance of N₂. Large atmospheric abundance of the minor species retards sublimation rates and accelerates deposition rates. If we assume that the atmosphere is well mixed, then the problem of finding the solid CH₄ and CO mass fluxes is reduced to finding the atmospheric abundance that globally balances mass flux. The challenge lies in defining how \( \dot{m}_i (i=CH_4 or CO) \) depends on the state of the surface and the atmospheric abundance, which we now address.

The simplest relationship between mass flux and atmospheric abundance follows Raoult's law (Trafton 1990, Owen et al. 1997), where the equilibrium partial pressure of gas \( i \) is simply \( p_i = V_i X_i \), where \( X_i \) is the mole fraction of the solid CH₄ or CO and \( V_i \) is its vapor pressure over the pure solid. For pressures other than \( p_i \), the mass flux is

\[
\dot{m}_i = -\frac{f}{4 RT_{frost}} \left( p_i - X_i V_i \right) \tag{5}
\]

where \( f \) is the sticking coefficient, and \( \bar{u} \) is the average thermal velocity of the atmospheric CH₄ or CO (Young 1994, Stansberry et al. 1996b, Spencer et al. 1997). Because \( V_{CH_4} \) is orders of magnitude lower than \( V_{N_2} \), rapid N₂ sublimation quickly and effectively creates a CH₄-dominated crust on the top surface of the frost (Trafton 1990, Stansberry et al. 1996b). If the CH₄-dominated crust is impermeable, then partial pressures of both CH₄ and N₂ are simply given by \( V_i X_i \). However, laboratory
experiments suggest that the CH$_4$ lag forms large grains rather than a solid cap, allowing N$_2$ to freely interact with the atmosphere through the granular CH$_4$-rich layer (Stansberry et al. 1996b).

An alternative relationship between mass flux and atmospheric abundance is the diffusive sublimation and condensation described by Stansberry et al. (1996b), following Monin-Obukhov similarity theory (Garratt 1992), analogous to Eq. 5:

$$m_i = -C_M \frac{u_s}{RT_{\text{frost}}}(p_i - X_i V_i)$$

(6)

where $C_M$ is the unitless mass transfer coefficient. Since the average gradient in the surface layer is globally neutrally stable, we set $C_M = C_H$ (Stull 1988, p. 263).

The global integral of the mass flux equals zero. Applying Eq. 5 or 6 twice, once globally averaged and once locally, allows us to find $p_i$ and the local mass fluxes.

**Model parameters:** We can specify the permeability, or the depth of CH$_4$ or CO lag needed to inhibit N$_2$ sublimation from underlying layers, to invoke either Eq. 7 or 8. A small permeability depth of 1 mm would reproduce the Trafton (1990) model, whereas a large permeability depth of 5 m would preclude any effect by the crust. The sticking coefficient in Eq. 7 is likely to be near 0.01 (Baglin et al. 2002).

### 3.3 Atmospheric radiative transfer

#### 3.3.1 Overview

We wish to develop the first model of the vertical structure of Pluto's atmosphere as a function of season. Because the atmosphere above the PBL does not significantly affect the volatile transport, we decouple the problems and calculate the vertical atmospheric structure after modeling the surface and planetary boundary layer.

The output of the PBL/Volatile Transfer models will include the atmospheric pressure, atmospheric temperature, and CH$_4$ and CO mixing ratios at some altitude above the PBL, each as a function of time in Pluto's year.

Our goal is to find atmospheric temperatures for which the energy equation balances at all altitudes (no net heating or cooling). We will modify an existing radiative-conductive energy balance model, written by Collaborator Yelle, that has been applied to Titan (Yelle 1991, Müller-Wodarg et al. 2002) and Jupiter (Yelle, Griffith, and Young 2001). The model from Yelle, Griffith, and Young 2001 (YGY) is being applied to Triton by PI Young as part of NASA Planetary Astronomy grant "Observationally constrained models of Triton's changing atmosphere and energetics" (Young et al. 2002). YGY uses a form of the Bader-Deuflhard semi-implicit extrapolation, a variation of Burirsch-Stoer integration for stiff problems (Press et al. 1992), for a specified temperature at the lower boundary and conductive heat flux at the upper boundary.

Because we are calculating the atmosphere at several seasons over a Pluto year, for several different model runs, we will study ways to speed up convergence to radiative equilibrium. One method is to start with a good initial estimate, and to this end we have developed a very rapid algorithm that simultaneously balances radiative heating vs. cooling in Pluto's upper atmosphere, and radiative heating vs. conductive cooling near the surface (Young 2004).

Our goal is thermal profiles in Pluto's atmosphere, not full chemical models. Nevertheless, we need mixing ratio profiles of CH$_4$ and CO to calculate heating rates. The CO mixing ratio is trivial; CO is expected to have a constant mixing ratio, because it has a long chemical lifetime and its molecular weight equals that of N$_2$, the dominant gas. Therefore, we can simply use a constant CO mole fraction as output from the PBL/volatile transfer model. The basic energetics/structure model will calculate the
CH$_4$ mixing ratio profile mainly from its photochemical destruction rate and its tendency toward diffusive separation in the heavier N$_2$, given its value at the top of the PBL. We will investigate more detailed chemistry to judge the importance of IR cooling by C$_2$H$_2$ or C$_2$H$_6$, or radio cooling by HCN. If we include these radiators in an extended model, this will involve a simplified set of chemical reactions, most likely adapted from Summers et al. (1997).

The calculation of radiative equilibrium gives the heating and cooling rates for the various processes in Pluto's atmosphere, as well as vertical profiles of temperature, pressure, and density in Pluto's atmosphere as a function of season. Temperature profiles are central to a wide variety of atmospheric questions, including escape rates, dynamics, chemistry, and haze formation.

### 3.3.2 Atmospheric conduction

**Significance of conduction:** For a body the size of Pluto, a lightcurve from a stellar occultation by an isothermal, clear atmosphere would have a long shallow runout with non-zero stellar flux at mid-event. The 1988 stellar occultation by Pluto had neither; rather it showed a "kink" at half light, indicating either haze absorption, a steep thermal gradient, or both (Elliot and Young 1992, Young 1994, Yelle and Elliot 1997). The 2002 occultation also lacks the long runout and zero midpoint flux, and, indeed, inversions of the 2002 lightcurve also show a steep thermal gradient (Sicardy et al. 2003). Regardless of the presence of hazes (Elliot et al. 2003), the atmospheric temperature of ~100 K at the occultation altitudes is much higher than the frost temperature (~40 K), and so there must be a thermal gradient between the occultation altitudes and the surface.

A thermal gradient implies a downward conductive heat flux (~0.035 erg/cm$^2$/s for gradients of ~10 K/km). In Pluto's lower atmosphere, where the atmosphere has large gradients, the cooling due to divergence of thermal conduction is a dominant contributor to the cooling in Pluto's atmosphere.

**Calculating thermal conduction:** For a small planet, heating from thermal conduction is:

$$H_{\text{cond}} = \frac{1}{r^2} \frac{\partial}{\partial r} \kappa r^2 \frac{\partial}{\partial r} T(r)$$

(11)

where $\kappa$ is the temperature-dependent thermal conductivity of N$_2$. This calculation is incorporated in the YGY energy-balance model, and will be transferred to Pluto.

**Model parameters:** The only parameter needed here is the thermal conductivity, which we take to be $\kappa(T) = 5.63 \, T^{4.12}$ erg/cm$^2$/s (e.g., Strobel et al. 1996).

### 3.3.3 IR/visible heating/cooling

**Significance of heating and cooling in the IR and visible.** The primary balance in much of Pluto's atmosphere is between heating by absorption of solar flux by CH$_4$ in the near IR (2.3 µm and 3.3 µm) and cooling by thermal emission of CH$_4$ at 7.7 µm (Yelle and Lunine 1989, also Strobel et al. 1996 fig 10).

**Calculating 2.3 and 3.3 µm heating by CH$_4$:** The existing YGY energy balance model calculates non-LTE absorption of solar IR radiation in the near-IR bands of CH$_4$ (3.3, 2.3, and 1.7 µm) and subsequent cascading to the $v_4$ (7.7 µm) band of CH$_4$. As part of our application of YGY to Triton, we are extending the n-stream calculations to include line-of-sight optical depths that are smaller than plane-parallel optical depths away from the zenith. This non-LTE calculation uses line lists from HITRAN 1996 (Rothman et al. 1998) and random band models (Wallace et al. 1974). The non-LTE effects are described by $P_{10}$, the probability that a V-T transition occurs during a collision (e.g., Yelle et al. 1989, Yelle 1991).
As part of the proposed work, we will update linelists to use HITRAN 2000 (Rothman et al. 2003), and incorporate any new information on \( P_{10} \) at Pluto's temperatures. We will also study ways to improve the computational efficiency of the absorption calculation, for example by taking advantage of how lines are dominated by Doppler widths at Pluto's low pressure.

**Calculating 7.7 µm cooling by CH\(_4\):** Our model calculates non-LTE cooling by CH\(_4\) at 7.7 µm using Rybicki's method (Yelle 1991). As for IR heating, for this project we will include non-plane parallel opacity and will update the CH\(_4\) line parameters (Rothman 2003) and V-T probability, as needed.

In the extension to the energetics/structure model, we will calculate first-order profiles of C\(_2\)H\(_2\) and C\(_2\)H\(_6\) abundance and evaluate whether cooling through their fundamentals is important for Pluto's temperature structure. If they are, the program to calculate C\(_2\)H\(_2\) and C\(_2\)H\(_6\) cooling is identical to the 7.7 µm cooling by CH\(_4\).

**Model parameters:** For this step, we need CH\(_4\) line lists, which we will obtain from HITRAN 2000 (Rothman et al. 2003). We will incorporate any new information on \( P_{10} \) at Pluto's temperatures; if none is available, we will follow Yelle and Lunine (1989) and let \( P_{10} \) range from \( 10^{-7} \) to \( 10^{-5} \). Changing \( P_{10} \) mainly affects the steepness of the thermal gradient in the lower atmosphere, which reveals itself in the location of the kink in the occultation lightcurve.

### 3.3.4 Radio cooling

**Significance of radio cooling:** CO cools Pluto's atmosphere by emission through pure rotation lines at radio wavelengths. A moderate amount of atmospheric CO lowers the temperature in Pluto's upper atmosphere by tens of degrees unless Pluto's atmospheric CH\(_4\) is at least 3% (Lellouch 1994), with CO dominating over near-IR CH\(_4\) heating/cooling for altitudes above ~five scale heights above the surface (Strobel et al. 1996).

**Calculating radio cooling:** The atmospheric energy balance equations we use calculate cooling by CO rotational lines with a modification of the cool-to-space equations (Yelle 1991) that is exact for LTE. We will also evaluate HCN cooling at radio wavelengths, using the same routines as the CO radio cooling.

**Model parameters:** This step uses line lists available from the HITRAN 2000 database (Rothman et al. 2003).

### 3.3.5 UV heating

**Significance of UV heating:** A fraction of the kinetic energy of molecules photodissociated by UV flux is expended in fueling atmospheric escape, and the contribution of UV heating to the atmosphere is roughly \( 5 \times 10^4 \) erg/cm\(^2\)/s (Strobel et al. 1996). At perihelion, previous models of Pluto's atmospheric structure have shown that Pluto's thermal structure is largely insensitive to UV heating (Yelle and Lunine 1989, Strobel et al. 1996).

At other seasons, when the densities of CH\(_4\) are lower and so UV absorption occurs closer to the surface, UV heating may be more significant. On Triton, which has less atmospheric or solid CH\(_4\) than Pluto, UV heating is an important contributor to the thermal structure (Yelle et al. 1991).

**Calculating UV heating:** The YGY model includes heating by globally averaged absorption of solar UV by N\(_2\), CH\(_4\), and others, including an efficiency factor to account for the contribution to atmospheric escape. At Pluto, interstellar Ly-\( \alpha \) is comparable to solar; for this project, we will use solar UV flux averaged over a solar cycle, and add the contribution from the interstellar medium.

**Model parameters:** We will assume a nominal UV heating efficiency of 0.5, but allow this parameter to range from 0 to 1.
This parameter is not expected to have much effect on the thermal profiles.

### 3.4 Model outputs and application

Our linked model produces outputs that can be compared directly against observations, allowing us to constrain the range of model inputs and produce useful and testable predictions from our model. We apply our model in several stages.

**Fig. 3.** Sample results from a simplified linked volatile transport/radiative transfer model (Young 2004), using frost distribution from Hansen & Paige 1996. Top panel: snapshot of model for 1993. Bottom panel: snapshot for 2002. The upper right of each panel is the thermal profile. The lower right is the resulting lightcurve, with the dashed line showing the lightcurve for an isothermal, clear atmosphere. The upper left of each panel shows the pressure (increasing down) at the surface and at 1250 km, where occultations probe. The lower left of each panel shows the distance from shadow center where an observer sees half-flux and the kink.

**Pilot model:** A pilot model will allow us to show a worked example of the way the model can be compared with observations. One such model was run for five frost distributions and thermal inertias, and the resulting predicted occultation lightcurves were presented at the 2004 DPS (Young 2004). This simple model did not include volatile transport calculations. Rather, it either assumed global N\textsubscript{2} frost coverage (with thermal inertia), or used frost distributions from Hansen & Paige 1996. The radiative transfer did not run to convergence, but approximately balances optically thin 3.3-μm CH\textsubscript{4} heating with optically thin 7.7 μm CH\textsubscript{4} cooling at the upper boundary and conduction at the surface. Despite these simplifications, one run (Fig. 3) qualitatively reproduced the observed changes in Pluto's atmosphere: (1) the increase in Pluto's atmospheric pressure, (2) the similarity of the temperature at high altitudes, and (3) the descent of the "kink" in the lightcurve from half-light to roughly the quarter-flux level. The purpose of the pilot model, and indeed the rest of the project, is to add more realistic physics into the linked model.

**Baseline model:** During model development, we will select nominal input parameters to test and exercise the model, leading to an initial baseline prediction.

**Sensitivity studies:** We will run our models over ranges of input parameters to study their effect on the outputs of the seasonal models of the atmospheric structure. We expect that some of the inputs are already well enough characterized that varying them over their expected reasonable range has little effect on the model results. These inputs can then be held constant at their nominal values, greatly decreasing the number and complexity of our model runs. Varying other inputs will have dramatic effects on the model outputs when varied over their input range. These are precisely the inputs that benefit most from the next step of comparing model outputs to observations.

**Observational constraints:** We can constrain the model inputs (those used in the previous step, sensitivity studies) based on observations of Pluto's observed time-
varying behavior. Most notable are the changes between the stellar occultations of 1988 (Hubbard et al. 1988; Elliot and Young 1992) and 2002 (Elliot et al. 2003; Sicardy et al. 2003). Two HST albedo maps, from 1994 (Stern et al. 1997) and 2002 (M. Buie, PI) should also be important. The latter HST map is being generated from a carefully planned series of dithered observations with high signal-to-noise, designed to get high resolution on Pluto. We expect to achieve 6 to 8 resolution elements across Pluto, or a 6x20 pixel map.

**Testable predictions:** The models will make predictions for the upcoming behavior of Pluto's surface atmosphere, which can be tested in the near future. A sensitive measure of the change in Pluto's atmospheric structure comes from stellar occultations. The upcoming crossing of the galactic plane by Pluto should greatly increase the number of high-quality occultations observed. It is particularly likely that new high-quality occultations will be observed before the end of 2007, midway through the timespan of this proposed modeling effort. The New Horizons spacecraft is planned to encounter Pluto in 2015, measuring the vertical profile of temperature and pressure from UV and radio occultations. UV occultations and airglow will also measure the CO and CH₄ atmospheric abundances. Visible cameras will record the albedo and color of Pluto's surface, and an infrared imaging spectrograph will measure the reflectance spectrum of Pluto's surface in the near-IR, giving the temperature, composition, and microphysical state of Pluto's surface at 7-10 km resolution. These observations will all be important tests of this linked model.

**4. IMPACT**

The result of our proposed linked model of planetary boundary layer/volatile transport and atmospheric energy balance will be to produce predictions of:

- surface composition, albedo, and microphysical state (e.g., N₂ phase, CH₄ mixing state) as a function of season, latitude, and longitude.
- frost deposition and sublimation rates, as a function of season, latitude, and longitude.
- atmospheric heating and cooling rates as a function of season and altitude.
- atmospheric temperatures, pressures, and densities, including surface temperatures, pressures, and densities as a function of season and altitude.
- atmospheric composition as a function of season and altitude. For the basic model we will include mixing ratios of atmospheric N₂, CH₄, and CO. For the extended model, we will include C₂H₆, C₂H₂, and HCN, if they prove to contribute to atmospheric cooling.

These predictions will have a broad impact on our understanding of Pluto's atmosphere:

- **Atmospheric energetics:** The seasonal atmospheric heating and cooling rates address a major goal of this project, to understand if or how the primary processes controlling energy balance change over Pluto's season.
- **Annual UV flux and surface photochemistry:** Evaluation of the competing processes of surface photochemistry and atmospheric laundering (Stern et al. 1983) depends on how solar and interstellar Ly-α flux is shielded by gaseous CH₄ and on the frost deposition rates.
- **Annual escape rate:** While models of Pluto's perihelion atmosphere suggest escape rates equivalent to the loss of 1 km of frost or more over the age of the solar system, the annually averaged escape rate may be much less if the temperature of Pluto's upper atmosphere drops at aphelion (Trafton et al. 1997). The escape rate is a function of the temperature, composition,
and density of Pluto's upper atmosphere, which are outputs from our models.

- **Predictions for Pluto observers**: A major goal of this project is to make predictions that are testable by occultations, and to guide decisions about occultation deployment and strategy. NIR spectroscopy of absorption by atmospheric CH₄ depends on the atmospheric CH₄ abundance and atmospheric temperature structure; the range of predictions produced in this program will suggest how often the atmospheric CH₄ should be measured, and what accuracy is needed to distinguish between competing models. Other predictions are listed in Table III. We intend to make these models as useful to the community as possible. As the models will produce more information than can be presented in refereed journals, we will make the outputs from these models available to others on request.

5. **RELEVANCE TO NASA OBJECTIVES**

The results of the proposed seasonal atmospheric model will be of interest and use to the New Horizons mission to Pluto, making predictions for and constraining the range of large-scale surface albedo patterns, surface composition, and atmospheric structure. The model results will be easily disseminated to the New Horizons team: represented on this proposal are the mission PI (A. Stern), Deputy Project Scientist (L. Young), Atmospheres Team Lead (R. Gladstone), Particles and Plasmas Team Lead (F. Bagenal), Deputy Geology/Geophysics Team Lead (J. Spencer), and Composition Team Lead (D. Cruikshank).

6. **WORKPLAN**

6a. **Task Summary and Schedule**

Following the advice of last year's reviewers, during the current year (funded under the 1-year award to our 2004 PATM proposal), we will produce a pilot model. The initial results of a simple model were presented at DPS 2004 (Young 2004). For the PBL/VT submodel, we will move existing VT code from Triton to Pluto, and add CH₄ and CO frost transport (but without a PBL). This will be done mainly by Co-I Spencer. We will also finish moving atmospheric RT code from Triton to Pluto. This will be done mainly by PI Young. We will run this pilot model with nominal input parameters to test the combined model.

During the first year of the proposed work, we will add the Planetary Boundary Layer to the VT model. This will include the calculations described in sections 3.2.3-3.2.5. This step will be done jointly by PI Young and Co-I Spencer, drawing on the experience of Co-I Rafkin. Also this year, we will add the simplified photochemistry and diffusion that will let us model the effect of atmospheric CH₄ mixing ratios that vary with altitude. This step will be performed by Co-I Bullock. This first complete model will be run with nominal parameters as a test and baseline.

By the second year, we spend most of our effort using the tools developed in the first year and presenting and submitting our results (PI Young, Co-I Spencer), while also extending the tools based on our experience in year 1. One probable extension is adding latitude and longitude in the PBL/volatile-transfer model (Co-I Spencer) to allow direct comparison with observed Pluto maps. Others might include improving composition profiles for the atmospheric energetic model (PI Young, Co-I Bullock, Co-I Rafkin).

The final year is spent applying the model developed during the previous two years, comparing model results to occultations, spectra, maps, and other observations, writing and submitting our results (PI Young, Co-I Spencer, Co-I Bullock, Co-I Young).
6b. Personnel Contributions
PI Leslie Young is a Research Scientist in the Department of Space Studies at Southwest Research Institute in Boulder. Dr. Young studies Pluto's atmosphere through occultations and high-resolution IR spectroscopy. Dr. Young has intimate familiarity with the radiative-conductive implementation we propose to use in this project (Yelle et al. 2000). As Principal Investigator, Dr. Young will have the primary responsibility for the tasks outlined in the above proposal. Dr. Young's specific contribution will be to modify and apply the models of atmospheric energetics and structure.

Co-I John Spencer is a Staff Scientist at SwRI. He developed the first detailed seasonal volatile migration model for Triton (Spencer 1990a), was the first to consider the effects of thermal inertia on volatile migration (Spencer and Moore 1992), and was first author of the chapter on seasonal volatile migration on Pluto in the U. Arizona Press Pluto book (Spencer et al. 1997). His specific contribution to this work will be to adapt his existing Triton seasonal volatile migration model to account for Pluto's different seasonal cycle, the effects of multiple volatiles, and a frost distribution that varies with longitude as well as latitude.

Co-I Mark Bullock is a Senior Research Scientist at SwRI, whose work on Venusian and Martian climate change includes fast radiative transfer and chemical algorithms. His specific contributions are in the tasks of speeding up the RT code and the first-order chemistry needed to calculate CH₄, C₂H₂, C₂H₆, and HCN profiles.

Co-I Scot Rafkin is a Senior Scientist at SwRI. He is an expert in numerical simulations of small-scale atmospheric phenomena in the Martian atmosphere, including boundary-layer convection and atmosphere-surface interactions. His specific contribution will be toward the addition of a planetary boundary layer to Co-I Spencer's volatile migration model.

Co-I Eliot Young is a Senior Research Scientist at SwRI, and has a long history observing and modeling Pluto. He was a coauthor of the chapter on seasonal volatile migration on Pluto in the U. Arizona Press Pluto book, and developed and ran a Pluto volatile transport model for Pluto's inhomogeneous surface (Young 1993). His particular expertise lies in mapping Pluto. His specific contribution is to compare our model results with the Cycle 12 HST Pluto albedo maps.

Collaborator Dr. Fran Bagenal is a professor in the Department of Astrophysical and Planetary Science at the University of Colorado, Boulder. She will use the model results to refine her models of Pluto's escaping atmosphere and solar wind interaction.

Collaborator Dale Cruikshank will provide thermal inertia information from the results of upcoming Spitzer observation of Pluto's thermal emission.

Collaborator Randy Gladstone will advise on which reactions to include in our calculation of mixing ratio profiles of important radiators.

Collaborator Alan Stern will participate in discussions about the volatile transport assumptions and results.
REFERENCES


FACILITIES AND EQUIPMENT

All of the facilities and equipment necessary for this project are available to us. Southwest Research Institute provides all of the computer resources, library facilities, and staff support needed to conduct the intended research. In particular, the computers available to PI Young support the software needed for this project, including C, Fortran, and IDL.