are examples of sources in which energy is supplied alternately on opposite sides but with a low 'flip-flop' rate[27], or whether they can still be understood in relativistic beaming models by modifying the basic unified scheme. When the unified scheme was developed, it seemed reasonable to assume that the extended emission is essentially at rest relative to the nuclear emission, which could be moving close to the velocity of light[10-13]. However, if the observed one-sideness of the lobe-dominated sources is due to relativistic beaming, then the velocities required for the extended emission are at least about $0.8c$ even for a source inclined at ~15° to the line of sight. For reasonable values[12,13] of the bulk Lorentz factors of the nuclear jets ($\gamma_c \approx 5$) and $F_c \equiv f_c(\phi = 90°) = 0.033$, the expected value of f_c using the expression given by Kapahi and Saikia[13] is 0.86 for $\phi = 15°$ if $\beta_e = 0$. This is clearly not consistent with the values observed for the lobe-dominated, one-sided sources. Modifying the basic unified scheme to include relativistic beaming of the extended emission changes the expression for the expected value of f_c to $1/[1+\{B_e(\phi)/B_c(\phi)\}\{(1/F_c)-1\}]$, where $B = (1-\beta \cos\phi)^{-(2+\alpha)} + (1+\beta\cos\phi)^{-(2+\alpha)}$, with subscripts e and c denoting extended and core (or nuclear) radio emission. Assuming the spectral indices of the core and extended radio emission to be 0 and 1 respectively, the value of f_c decreases from 0.86 when $\beta_e = 0$ to 0.12 when $\beta_e = 0.8$ for the same set of parameters mentioned earlier. Here, the beamed extended emission dominates the beamed core emission, which is intrinsically weaker. It is thus possible to understand the brightness asymmetry of the lobes in the lobe-dominated, one-sided sources, and also their low values of f_c in the unified scheme, if we are prepared to widen it to include very significant beaming of the extended emission for a small fraction of sources.

However, besides necessitating such changes in the scheme, there are other problems with this explanation. Even if the hot-spots are moving with such high velocities, it is difficult to understand the asymmetry of the well developed lobes (Fig. 1), which should comprise mainly backflow from the hot-spots. Also, if there is a range of hot-spot speeds extending up to ~$0.8c$ for a small fraction of sources, it is not clear why there are no intermediate cases with, say, $f_c \approx 0.5$ and degrees of asymmetry of several hundred. Further observations, including those aimed at detecting very weak diffuse emission on the opposite side of the one-sided sources, are clearly required to help clarify the situation.

An important diagnostic to distinguish between different explanations for these lobe-dominated, one-sided sources is likely to be provided by VLBI observations of their nuclei. If they are indeed inclined at small angles to the line of sight, rather than being simply intrinsically one-sided sources observed at large viewing angles, one would expect to find evidence of phenomena more characteristic of core-dominated radio sources. These include significant misalignments between the VLBI structures and the arcsecond-scale structures, which are well aligned in lobe-dominated sources[1,6,7], and evidence of superluminal motion[8]. One would also expect to observe significant variability of the core flux density, lack of any correlation of core polarization vector with the radio-source axis[28] and low equivalent width of the emission lines[29]. On the other hand, if the VLBI jets are on the opposite side to that of the arcsecond-scale structure, these sources would provide perhaps the best examples of the 'flip-flop' model. In this model, energy is supplied alternately on opposite sides but, averaged over its lifetime, the source appears reasonably symmetric. The timescale for the energy to change direction would have to be at least ~10^5 years for the lobe-dominated, one-sided sources. ☐

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Evidence for a molecule heavier than methane in the atmosphere of Pluto

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THE recent occultation of a 12th magnitude star by Pluto provided a unique opportunity for studying its atmosphere. Analyses of measurements made at the Hobart observatory in Australia and the Kuiper Airborne Observatory (KAO) have been published[1,2]. It is generally agreed that Pluto possesses a substantial atmosphere, with a surface pressure of ~10 μbar. Both occultation measurements are sensitive primarily to the atmospheric conditions at the 1-μbar level. Analysis of the Hobart data reveals an atmospheric scale height of 46–57 km at a radial distance of 1,240–1,290 km, whereas the scale height derived from the KAO data is 59.7 ± 1.5 km at 1,214 ± 20 km. The existence of an optically thick dust layer along the line of sight at the limb has been inferred from the KAO measurements, raising doubts about the true surface radius of Pluto[2]. The measured scale heights are consistent with a purely methane atmosphere at a temperature of 50–61 K for the Hobart data[1] and 67 ± 6 K for the KAO data[2]. These values are close to the surface temperature[3]. Here we examine the energy balance in the atmosphere and conclude that the temperature near 1 μbar is ~100 K rather than the surface temperature; consequently, the mean molecular weight of the atmosphere is close to 25 a.m.u., and a molecule heavier than (and in addition to) methane must be present in the atmosphere.

Methane, or methane ice, has been detected spectroscopically in the Pluto atmosphere but it is difficult to determine the atmospheric abundance from these data[4]. Upper limits of ~25 μbar have been placed on the gaseous abundance of CH_4 from the infrared spectrum[3,5]. However, even small amounts of CH_4 are sufficient to cause substantial heating of an atmosphere. The CH_4 molecule possesses a number of strong vibrational bands in the thermal infrared and is believed to be a major source of stratospheric heating on the outer planets and Titan[6-8].

Therefore, it seems likely that methane will also be an important heating agent for Pluto's atmosphere and that the atmospheric temperature may be elevated above the surface temperature. We study the possibility of significant atmospheric heating due to the presence of CH_4 by constructing thermal models for Pluto's atmosphere, including infrared heating and cooling through the CH_4 bands and thermal conduction to the surface.

The strongest CH_4 bands occur at 3.3 and 7.8 μm. The 7.8-μm band, which connects the ground state to the fourth vibrational (ν_4) level, is the lowest-lying fundamental and, at the low temperatures on Pluto, will be the dominant channel for radiant energy loss. Examination of the solar spectrum and band strengths reveals that the bulk of the heating will occur in the 3.3-μm band, which connects the ν_3 level to the ground state, although the bands at 1.7 and 2.3 μm may make an important contribution[7,8]. Because of the low temperatures and low collision rates, the atmosphere will be far from thermodynamic equilibrium and we must solve the energy-transport equation to determine the atmospheric temperature profile. The steady-state energy transport equation, ignoring convective terms, is

$$-\frac{\mathrm{d}}{\mathrm{d}z}\kappa\frac{\mathrm{d}T}{\mathrm{d}z}=Q-L \tag{1}$$

where T is the temperature, κ is the thermal conductivity, z is the altitude, Q is the heating rate, and L is the radiative cooling rate. Equation (1) ignores effects such as the variation of gravity with altitude and adiabatic cooling, which are important in the thermosphere, because our intention is to estimate the temperature in the bottom layers of the atmosphere. The validity of these assumptions is discussed later.

The radiative cooling rate in an optically thin atmosphere may be expressed as

$$L=g\varepsilon nh\nu A_{\mathrm{R}}\exp\left(-\frac{h\nu}{kT}\right) \tag{2}$$

where n is the number density of the radiating constituent, $h\nu$ is the energy of the emitted photon, k is Boltzmann's constant, g is a factor that accounts for the statistical weights of the upper and lower states, and ε represents the efficiency at which vibrational energy is converted into radiation and is determined by the relative values of the radiative decay rate and vibration-translation (V–T) reaction rate,

$$\varepsilon=\frac{P_{10}Zn_{\mathrm{a}}}{P_{10}Zn_{\mathrm{a}}+A_{\mathrm{R}}} \tag{3}$$

where n_{a} is the atmospheric density, Z is the collision rate, P_{10} is the probability that a V–T transition occurs during a collision, and A_{R} is the Einstein coefficient for the band in question. V–T probabilities for CH_4-CH_4, CH_4-CO, and CH_4-N_2 collisions at room temperature are 5.3×10^{-5}, 9.4×10^{-6} and 5.5×10^{-6} respectively[9]. At the low temperatures on Pluto the V–T probability is likely to be smaller, but experimental data are lacking and extrapolations are uncertain. To make the extrapolation we follow the procedure outlined by Lellouch *et al.*[10], which results in a decrease by a factor of ~10 in P_{10} in extrapolating from 300 K to 100 K. The factor of 10 is adopted as an indication of the uncertainty in P_{10}, and we examine the dependence of the thermal-structure calculations on this quantity. We note that pressure-induced transitions are far too weak to cause significant cooling at pressures of ~1 μbar.

The radiative heating rate is given by

$$Q=\frac{\pi F}{4}\varepsilon nB \tag{4}$$

where πF is the solar flux at 3.3 μm, B is the band strength, and the factor of $\frac{1}{4}$ accounts for global averaging. In equation (4), ε is given by an expression similar to equation (3), although the probability for deactivation and the radiative decay rate may be different because heating and cooling occur through different bands. The assumption of optical thinness for the heating and cooling rates may be justified in the manner described by Dickinson[11].

Aerosol heating is thought to be an important factor in the stratospheric thermal balance on Titan and the outer planets, and may also play a role on Pluto[7-9]. If aerosol heating is important it could mean that the temperatures are significantly higher than those calculated here. At present there is insufficient information to quantitatively evaluate this possibility.

Using equations (2) and (4) for the heating and cooling rates, we solve equation (1) for the temperature profile. We assume that the atmosphere is composed of CH_4 and a species of atomic weight 28 in diffusive equilibrium. (We use a 3.3-μm band strength of 0.30 μm cm-atm^{-1} and a solar flux of 23 erg cm^{-2} s^{-1} μm^{-1}. The radiative decay rate of the 7.8-μm band is 2.56 s^{-1} whereas a radiative decay rate of 4.24 s^{-1} is adopted for the group of bands centred at 3.3 μm.) We adopt the 10-μbar level as the lower boundary and the ~10^{-2}-μbar level as the upper boundary. The heat flux at the upper boundary is set to zero despite the fact that most of the solar extreme-ultraviolet energy will be deposited above this level. This is because a large fraction of the energy deposited in the thermosphere may be lost through hydrodynamic escape of the atmosphere[12]. Solution of the hydrodynamic equations is necessary to determine what fraction of the solar extreme-ultraviolet energy flows downward into the lower atmosphere, but such a calculation is beyond the scope of this paper. Calculations with a downward heat flux at the upper boundary show that conditions near 1 μbar are insensitive to thermospheric heat flows of 5×10^{-4} erg cm^{-2} s^{-1}. The temperature and pressure at the surface of Pluto are uncertain and the values given above are simply reasonable estimates. Fortunately, the calculations demonstrate that the conditions at the lower boundary have a very small effect on the conditions at 1 μbar, provided that the surface pressure is greater than ~3 μbar.

Results of the thermal-structure calculations are summarized in Table 1 and an example is shown in detail in Fig. 1. We note that the temperature profile is close to isothermal in the 1-μbar region, as assumed in the occultation analysis. In general the temperature at 1 μbar is insensitive to both P_{10} and the CH_4 mole fraction. P_{10} has little effect because the heating and cooling rates depend on this quantity in the same way, and consequently lower heating efficiencies are accompanied by lower cooling

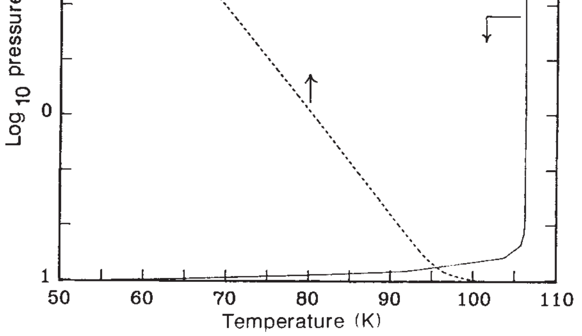

FIG. 1 The temperature profile and infrared heating rates for a model atmosphere with $P_{10}=10^{-6}$ and a CH_4 mole fraction of 10%.

efficiencies. Similarly, both heating and cooling rates are directly proportional to the methane mole fraction and its effects tend to cancel. These arguments break down when the radiative time constants become so small that the conduction term in equation (1) becomes important and heat flows to the surface faster than it is radiated away. In our models this occurs only for the smallest combinations of P_{10} and CH_4 mole fraction.

To assess the dependence of thermal structure on the infrared heating rates, we performed calculations with heating rates reduced by a factor of 3. The temperature at 1 μbar decreased by 6% for the model with a CH_4 mole fraction of 10% and $P_{10} = 10^{-6}$; consequently, the approximations used to drive these rates should not cause much concern. We have also modelled the effects of adiabatic cooling on the thermal structure. We find that an escape flux of less than 1×10^{12} cm^{-2} s^{-1}, referred to the surface, produces no noticeable effects near 1 μbar. This flux is much larger than previously estimated upper limits to the escape rate[12].

We can use the measured scale height with the thermal-structure calculations to infer the mean mass of the Pluto atmosphere near 1 μbar. A temperature of 106 K and scale height of 59.7 ± 1.5 implies a mean mass of 25 ± 3, which is much heavier than CH_4 and implies that the major atmospheric constituent is a heavier gas such as CO, N_2 or argon. If the heavier gas is argon, the error bars on the scale height imply a CH_4 mole fraction between 40 and 65%. If the heavier gas has a molecular weight of 28 the upper bound on the CH_4 mole fraction is 42%. The lower bound is determined by the amount of CH_4 required to produce a temperature on the order of 100 K. From the results in Table 1 we estimate a very conservative lower limit of 0.1%.

To estimate the relative abundance of CH_4 and the heavier gas in the atmosphere and surface requires modelling the relative escape fluxes and photolytic/cosmic-ray destruction rates of these gases; this requires more-detailed knowledge than we have at present. Likewise, it is not clear whether the lower atmosphere of Pluto is well mixed, whether both constituents are in equilibrium with surface ices, or whether diffusive separation of the gaseous components has significantly enhanced CH_4 at the occultation level. The range of methane compositions derived above (0.001-1), however, is sufficiently large that these considerations are not critical for the discussion of cosmochemistry that follows.

Based on solar elemental abundance, the most likely candidates for the heavy-gas component of Pluto's atmosphere are argon, carbon monoxide and molecular nitrogen. Models of the incorporation of argon and nitrogen into outer-Solar-System bodies by direct condensation or clathration predict that the argon-to-nitrogen ratio should be ≤ 0.1, the solar elemental ratio; we have no evidence to the contrary (for example, from Titan[4]) and hence we assume that argon is a secondary component. The presence of a predominantly nitrogen-methane atmosphere on Titan would suggest that nitrogen is a good candidate for the heavy gas. However, the uncompressed density of Titan (1.5-1.6 g cm^{-3}) is low relative to that of Pluto (>1.99 g cm^{-3}); also Titan's position as a regular satellite of Saturn suggests a different origin for Titan than for Pluto[4,13]. In particular, Titan formed in a water-rich nebula, and incorporated methane and ammonia, which over the age of the Solar System was converted to molecular nitrogen by photolysis and shock heating of its atmosphere[4]. Pluto's high density and position as a solar-orbiting body suggest, however, that it was formed in the relatively water-poor solar nebula[15]. Models predict that carbon monoxide was the dominant carbon-bearing molecule in the nebula. If so, then the heavy gas in Pluto's atmosphere could be carbon monoxide. The question may then be posed: is the inferred ratio of methane relative to carbon monoxide, q_P, consistent with an origin in the solar nebula?

TABLE 1 Temperatures (K) at 1 μbar

P_{10} \ n/n_a	100%	10%	1%	0.1%
10^{-5}	106	106	106	101
10^{-6}	106	106	102	63
10^{-7}	106	102	63	56

The most plausible mechanism for bringing these gases into Pluto during its formation is trapping in water ice by adsorption or clathration, as nebular models do not predict temperatures low enough to condense the pure solids of these species[13]. Let q_N be the ratio in the solar nebula of CH_4 to CO. The values of q_N and q_P are not identical because the gases are trapped to differing extents in water ice, determined by the number of available adsorption sites and the polarizability of the two gas species. A conservative fractionation factor q_N/q_P is 0.1-0.01. Hence, based on the atmospheric abundance ratio derived above (00.001-1), q_N could range from 10^{-1} to 10^{-5} in the region of the solar nebula from which Pluto formed. These values are consistent with chemical models for the solar nebula[16,17]. Moreover, as the water abundance is tied directly to the carbon monoxide abundance in such nebular models, the density of Pluto can be calculated for this range of q_N values[14]. One finds a Pluto density of 1.99-2.08 g cm^{-3}, consistent with the lower bound on the density derived from Pluto-Charon eclipse data[3] (which is only a lower bound because of uncertainties in the surface radius and the relative densities of Pluto and Charon[18]). It is interesting that q_P overlaps with the methane/carbon monoxide ratio (~ 0.3) found in comet Halley[17]. From those data, it has been concluded that the final stages of formation of Halley also took place in the solar nebula[17]. Although we cannot assert that the atmospheric ratio is reflective of the bulk ratio in Pluto, the arguments presented above illustrate the expectation that Pluto should have a substantial amount of CO.

The assumption that the heavier gas in Pluto's atmosphere is largely CO is consistent with cosmochemical models of the solar nebula and Pluto's density. If our interpretation is correct, nebular chemical models would predict the presence of molecular nitrogen in Pluto's atmosphere, at an abundance roughly 10-100 times less than that of carbon monoxide and an argon abundance of $\sim \frac{1}{10}$ of that of nitrogen. Although we cannot rule out a purely methane-nitrogen atmosphere, like that of Titan, the bulk density of Pluto, its position as a solar-orbiting object, and the results of the comet Halley measurements do not support this.

Much of this discussion of Pluto's thermal structure can be applied directly to Triton, which may be approximately the same size, and also shows evidence for surface, and hence atmospheric, methane. Both the composition and temperature of Triton's atmosphere will be measured during the Voyager encounter, providing a potential test of the ideas presented here. ☐

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