Thermal Escape of Planetary Atmospheres

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presented to
Modeling Atmospheric Escape Workshop
Charlottesville, VA
February 27, 2012
Outline

- Intellectual history of escape, briefly
- Overview of Current Escape Problems?
- Summary and what do we do now?
The first thoughts on this subject were from the end of the 19th century, in conjunction with the development of kinetic theory. A good reference is Jeans' book The Dynamical Theory of Gases. He developed this formula, based on some extreme assumptions. I often wonder if Jeans expected the formula to be accurate. Legions of researchers have assumed it was accurate, even though the conditions for applicability were never well established. The most important condition, for the purposes of this talk, is that the escape process does not affect the temperature structure of the atmosphere.
If there is an escape flux, the atmosphere is not static or isothermal.

Using standard kinetic theory we can calculate the changes in the distribution function due to these effects.

We can then calculate the flux of escaping molecules and compare to Jeans.

The temperature gradient has a dominant effect.

One way to establish the conditions for use of the equation is to look at the next order corrections. This was done in a 2009 paper by Jun Cui where he looked at the modifications to the Jeans escape rate using the 13-moment approximation rather than the Euler equations (5 moment). The paper was on escape of H2 from Titan and the correction factor is large and strongly depends on the thermal gradient in the atmosphere. We got a factor of 3 correction in that paper, but there have been some changes to the atmospheric data and newer calculations give a factor of 1.5, which is in excellent agreement with DSMC calculations that were presented this summer by O.J. Still this approach only works for low escape rates. It's not wise to extend the moment approach to much higher levels because it gets too unwieldy. The traditional approach has been to switch modes and look at a fluid approach to escape.
The Great Parker-Chamberlain Debate

Parker (Solar Wind): The solar atmosphere behaves as a fluid and accelerates to supersonic speeds.

Chamberlain (Solar Breeze): The solar atmosphere can be treated kinetically or hydrodynamically. Escape is mild and sub-sonic in either fluid of kinetic descriptions.

This was first done in conjunction with the solar wind and led to the Great Parker-Chamberlain debates. Something to remember:
1) Parker’s models were not a prediction but an attempt to explain an inference from observations. Early arguments about the supersonic solar wind were based on observations of comet tails and aurora. The Mariner 2 observations verified these conclusions.
2) Neither Parker nor Chamberlain were able to convince the community of the correctness of their approach through physical arguments alone. We have to conclude that neither argument was compelling enough. The argument is often described as a disagreement over whether the solar wind was supersonic or not. That’s true, but it is an over simplification. In essence, it was an argument over boundary conditions.
Boundary Conditions Dictate Character of Solutions

\[ E = E_\infty \left[ \frac{(2\kappa_0 G m M)^2}{k^2 (E_0 T_0)^5} \right]^\frac{1}{2} . \]

E >> 0, Parker
E = 60, Whang & Chang
0 < E < 60 Durney
E → 0, Chamberlain

Chamberlain’s solutions correspond to the energy flux at infinity carried purely by thermal conduction, Parker’s there’s a contribution from the kinetic energy of the molecules. This has been well established in numerous subsequent paper. These figures are from a paper by Roberts in the early 1970s and it shows solutions for different values of the integration constant \( E_{\text{inf}} \). Each of these choices also corresponds to an asymptotic from for the temperature gradient. All of these solutions are physically possible. For the solar wind the constant was esssentially determined by observations, at least that what was thought at first.
In my view, neither had a very good argument for the integration constant. Parker picked it essentially to explain an observation. Chamberlain chose his value to achieve consistency with an incorrect application of kinetic theory.
There is now a broad consensus that the solar wind is not heated by thermal conduction.
Leftover Questions

- The wind is supersonic, but not well described by Parker’s solution. It seems that there are internal sources of energy and momentum. Does it affect the arguments about boundary conditions?
- How do we determine the correct boundary condition from physical arguments?
- The solar wind (and planetary winds) are far more complicated than the stories told in textbooks.

In fact, this is a silly question because the equations do not apply to infinity. The real question is how do we pick boundary conditions that give the best solutions in the regions that we care about, in the regions for which the equations do apply?
Energy Limit for Planetary Atmospheres

• The primary consequence of strong escape is to modify the thermal structure. Typically, the extra terms in the vertical momentum equation are not important.

• For non-heated atmospheres (if there are any), thermal conduction limits escape; for heated atmospheres the solar heating rate limits escape.
In fact, a much simpler, and better, limit is that the energy carried by escape must be less than the solar EUV energy absorbed in the upper atmosphere.
Disappearing Pluto

Estimated mass of Pluto as a function of time. The dots are the experimental data, the equation is plotted as the solid line, which is the best fit curve on which the theory is developed.

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Briefly describe the Venus runaway scenario.
The energy limit for the escape of H$_2$ is more severe than the diffusion limit. H$_2$ builds up and perhaps dominates in the lower atmosphere.
Diffusion and Terrible Titan

- The Ar data imply $K=3\times10^7$ cm$^2$s$^{-1}$, similar to values in other atmospheres.

- Adopting this $K$ implies that the CH$_4$ profile can only be fit with an enormous escape flux.

Those are examples of where thermal escape affects atmospheric evolution, but there are also places where escape can be studied today.
Hydrodynamic Escape from Titan?

Titan’s hydrodynamically escaping atmosphere
Darrell F. Strobel
Extra-Solar Planets

An extended upper atmosphere around the extrasolar planet HD209458b
A. Miel-Madjar, A. Leconte, J. R. Deacon, G. E. Schneider, R. Forget, G. Slab負' & M. Mayor

Aeronomy of extra-solar giant planets at small orbital distances
Roger V. Yelle
Lots of Escape Models
Lammer et al., Garcia-Munoz, Tian et al., etc..

Koskinen et al. (2012)
Murray-Clay et al. (2009)
The equations do not apply at infinity. The fluid approximation breaks down, other processes neglected in the equations become dominant. In fact, this happens quite close to the body in question, perhaps just several radii away. So, what are we doing? We’re trying to find the boundary conditions for a highly idealized, unrealistic model that gives a good approximation to the real situation in a limited region. This requires judgement and the answer may be different in different cases. Don’t take the solar wind analogy too far.
Questions about Modeling EGPs

- What are the right boundary conditions?
- What level of sophistication is justified in modeling these atmospheres?
  - grey or wavelength dependent?
  - include tides or model them badly?
  - To what distances?
- Escape rates can be calculated with more confidence than atmospheric structure. Can we believe structure?
Fluids & Molecules & DSMC

Volkov et al. (2011)

Modified Jeans Escape for $\lambda > 3$

Fluids fail $Kn > 0.2$
Closing Thoughts

- We cannot include all the relevant physical processes in the DSMC models, so how do we use these results to inform less rigorous but more comprehensive calculations in the fluid or kinetic regimes?
- Do the DSMC models give us (finally) a physically-based argument for the proper boundary conditions?