Balloon Data and the Temperature Profiles of Solar System Bodies

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Atmospheric temperature measurements during a balloon flight can provide the basis for an undergraduate laboratory activity investigating physical and chemical processes in the Earth's atmosphere and the comparison of temperature versus altitude in the atmospheres of solar system bodies. Data from a launch on 6 November 2010 indicate the effects of the Earth's surface, the lapse rate in the troposphere, the altitude of the tropopause, and the increasing temperature of the stratosphere. The data are also compared to the temperature profiles of Venus, Mars, and Titan. Processes in the atmosphere of Titan are discussed.

Nomenclature

C_p	=	specific heat at constant pressure for air
g	=	acceleration due to gravity
$\left.\frac{dT}{dz}\right\|_a$	=	dry adiabatic lapse rate

I. Introduction

ONE of the basic measurements of the Earth's atmosphere made during balloon flights is the temperature as a function of altitude. The temperature profile of the Earth can be measured up to an altitude of approximately 30 km using inexpensive balloon flights. This profile can then be used as the data in an undergraduate laboratory activity. The physical and chemical causes for the changes in atmospheric temperature as a function of altitude can be examined. Similarities and differences among the temperature profiles of the Earth and other solar system bodies can then be examined.

The troposphere is the lowest layer of the Earth's atmosphere extending to an altitude of approximately 15 km. Weather occurs in this layer. The air is heated by the solid Earth below and the temperature usually decreases with altitude. The **negative** of the measured temperature change with altitude is known as the environmental lapse rate and averages about 6.4 K/km in the troposphere.[1] When the air is stirred by winds or when little or no surface heating occurs, the lapse rate is small. During periods of strong surface heating, the lapse rate is high. The lapse rate controls the stability of the atmosphere with respect to vertical convection. An air bubble will expand and cool as it rises and that will control the convection. If a rising bubble of air is warmer than the air it rises into it will continue to ascend. If the air bubble is cooler than the air it ascends into, it will cease rising and sink. The rate at which the air bubble cools will control the convection. The dry adiabatic lapse rate near the surface of the Earth is [2]

$$\left.\frac{dT}{dz}\right|_a = -\frac{g}{C_p} \tag{1}$$

This value works out to approximately 9.76 K/km.[1,2] This rate is referred to as dry because no condensation is occurring and adiabatic because no heat enters or leaves the bubble. If the environmental lapse rate exceeds 9.76 K/km, the air is absolutely unstable and convection will occur. The lower limit of cooling is set by the saturated adiabatic lapse rate. At the SALR condensing water vapor releases the latent heat of vaporization and reduces the rate of cooling. This rate depends on the temperature and is not a constant. Cooler air has a higher SALR and warmer air has a lower SALR. If the environmental lapse rate is less than 4 K/km, the lower limit for the SALR, the

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atmosphere is absolutely stable. At intermediate lapse rates the stability depends on the moisture content of the air, the relative humidity. If the air bubble reaches the condensation temperature, the latent heat of condensation will be released as the water vapor condense, the bubble will cool more slowly and the lapse rate will decrease. Occasionally an inversion will occur near the surface of the Earth with the temperature increasing with altitude. Such inversions stifle convection and reduce the lapse rate in the troposphere.

The troposphere ends at the tropopause where the lapse rate is 0 K/km for a span of several km. The temperature ceases to decrease and begins to increase in this region because it is heated from above. In the stratosphere from an altitude of 15 km to 50 km (above the tropopause) chemical compounds, especially ozone (O_3), absorb ultraviolet radiation from the Sun and warm the atmosphere. Our balloon flights normally rise to an altitude of 25 – 30 km and enter the lower stratosphere. Above the stratosphere the temperature falls in the mesosphere and rises again in the thermosphere. These regions are above the altitude to which our balloons can achieve and will not be discussed further in this paper.

The Earth, Venus, Mars, and Titan (the largest satellite of Saturn) have solid surfaces and considerable atmospheres. The Earth's atmosphere is about 78% nitrogen (N_2), 21% oxygen (O_2), and 1% argon (Ar) by volume. The atmospheric pressure at the surface of the Earth is 1010 hPa. Venus' atmosphere is 96.5% carbon dioxide (CO_2) and 3.5% nitrogen with a surface pressure of 9.2 MPa. Similar in composition to Venus' atmosphere the Martian atmosphere is 95.3% carbon dioxide, 2.7% nitrogen, and 1.6% argon with a surface pressure of 6 hPa. Titan's atmosphere is 90 – 97 % nitrogen, 0 – 6 % argon, and 0.5 – 4% methane (CH_4) with a surface pressure of 1500 hPa. Titan's atmosphere is similar to the Earth's in that the main constituent of its atmosphere is nitrogen. See Ref. 3 for more extensive information on the atmospheres of solar system bodies.

The lower atmospheres of these solar system bodies show similarities and differences to the Earth's lower atmosphere. The temperatures of the atmospheres of Venus, Mars, and Titan all decrease with altitude near the surface. Near surface inversions have not been measured on other bodies but the data are fairly limited. The adiabatic lapse rate for Titan is 1.3 K/km. [2]

The atmospheres of Venus and Mars do not show a stratosphere in which the temperature increases and above which the temperature decreases. Due to the chemical make-up of Venus' and Mars' atmospheres there is no mechanism on these planets for substantially warming the atmosphere in intermediate layers such as the ultraviolet (UV) absorption by ozone (O_3) in the Earth's stratosphere. Titan however does show stratospheric warming due to the presence of CH_4 which absorbs the solar UV

II. Equipment and Measurements

The StratoSAT command module was used to measure the temperature during a balloon flight from Morris, MN. The flight achieved an altitude of 32 km. The temperature sensing circuit is very simple and uses an LM 335 as the temperature sensing device.

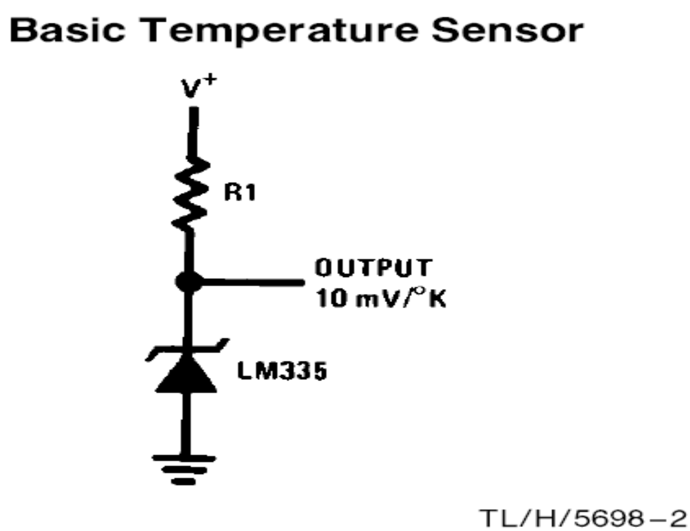

Figure 1. The temperature measurement circuit.[4]

The temperature sensing of the LM 335 is carried out by a Zener diode with a temperature sensitive breakdown voltage. The output voltage representing the temperature is then digitized and transmitted along with the GPS information. The voltage representing the temperature (T(V)) is then converted to the temperature in Kelvin (T(K)) using

$$T(K) = T(V) * 5.00/1023 \tag{2}$$

The uncertainty of LM 335 temperature measurements is ± 1 K.

III. Results and Discussion

The measured temperature versus altitude data are shown in Figure 2. The launch occurred on Saturday, 6 November 2010, at 8:52 am. At this time the inversion up to an altitude of about 2 km is obvious. From about 2 to 4 km the temperature is approximately constant. Above 4 km the lapse rate in the troposphere was 3.2 K/ km. This lapse rate is very low and indicates an absolute stability of the atmosphere with regard to convection. The average lapse rate in the troposphere is ~ 6 K/km. The change in temperature with altitude in the stratosphere is +1.5 K/km indicating the stratospheric heating due to heating through the absorption of UV radiation by O_3. Chlorine radicals in the stratosphere, derived from the photo-dissociation of chlorofluorocarbons and hydrochlorofluorocarbons, have chemically depleted O_3 in the stratosphere. The chemical reactions involved in ozone depletion indicate the very different chemistry that can occur in the presence of UV radiation in the stratosphere compared to the troposphere. UV does not penetrate into the troposphere.

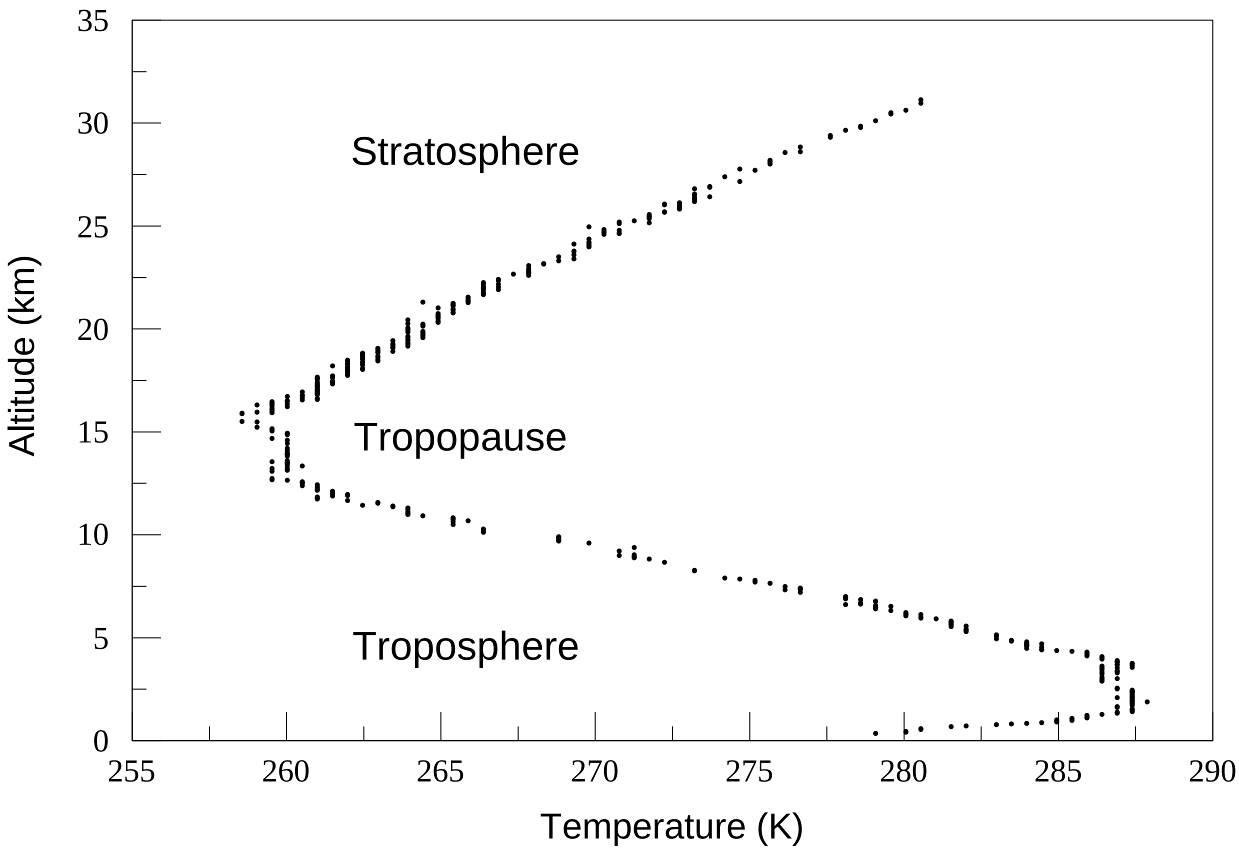

Figure 2. Altitude versus temperature. The layers of the troposphere, tropopause, and stratosphere are indicated. The near surface inversion rises to about 2 km.

IV. Comparison with Titan

On 14 January 2005, the Huygen's spacecraft descended to the surface of Titan at a latitude of 10^o S. The temperature profile for the lower atmosphere of Titan is shown in Figure 3.[5] As with the Earth, Venus, and Mars the temperature decreases with altitude near the surface of the body. At an altitude of 55 km the temperature begins to increase. It is thought that at this height and above CH_4 in the atmosphere absorbs solar UV and photo-dissociates. The stratosphere of Titan is then heated by the photo-dissociation from above. The photo-dissociation leads to various chemical reactions that could not occur on the surface of Titan. These reactions produce complex hydrocarbons and hydrocarbon-nitrile aerosols known as tholins. The tholins are thought to generate the orange haze observed in Titan's atmosphere. These physical and chemical processes occur in and above Titan's stratosphere. The temperature data from higher in Titan's atmosphere indicate a small, but not completely absent, mesosphere.

The observed environmental lapse rate near the surface of Titan is less than 0.85 K/km. The dry adiabatic lapse rate at the surface of Titan is 1.30 K/Km.[1] Further information about the methane content is needed to make definite conclusions about the possibility of convection in Titan's lower atmosphere.

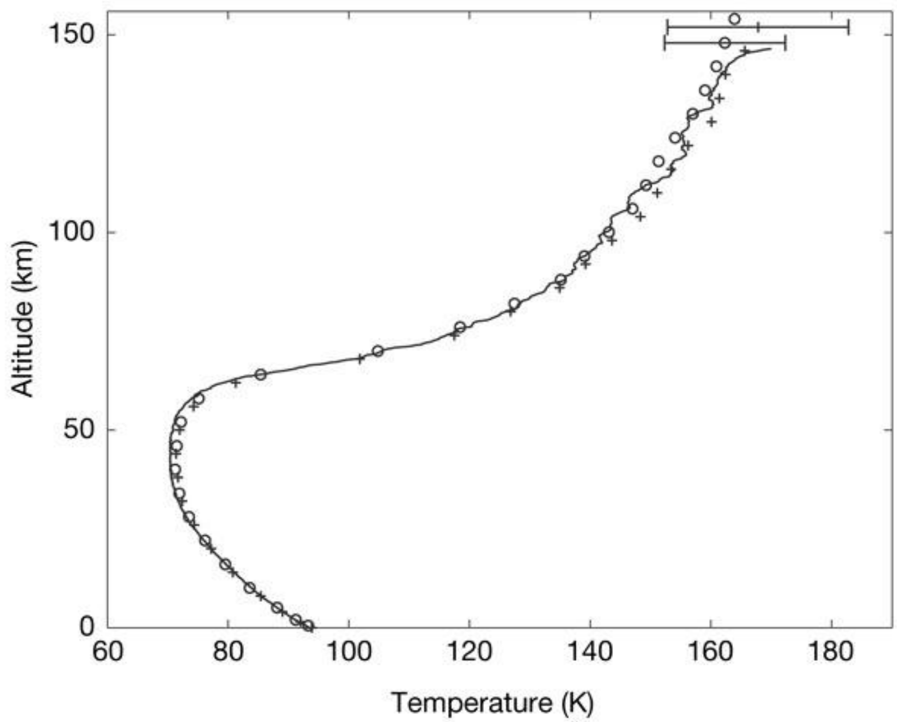

Figure 3. Altitude versus temperature for Titan. The tropopause exists from approximately 40 - 55 km altitude on Titan. [5]

V. Laboratory Activity

A laboratory activity based on the altitude versus temperature data from a high altitude balloon flight has been developed and is attached as the appendix.

VI. Conclusion

Temperature data from high altitude balloon flights can be used as the basis for laboratory activities studying the atmospheric physics of the Earth and comparing the atmospheric temperature structure of the Earth with other solar system bodies. Ballooning activities provide students with unique opportunities to acquire and analyze data and to make qualitative and quantitative comparisons of physical and chemical aspects of the atmospheres of solar system bodies.

Appendix

A Laboratory Activity Based on Balloon Data and Temperature Profiles

Objective: to measure the temperature in the regions of the Earth's atmosphere investigated by a high altitude balloon flight and compare and contrast these data with information from Venus, Mars, and Titan (other solar system bodies with solid surfaces and substantial atmospheres)

Background: From the INTRODUCTION TO THE PAPER ABOVE

Procedure:

1. Obtain the data file from the balloon flight.

2. Convert the voltage representing the temperature, column A3, into T(K), the temperature in Kelvins.

$$T(K) = A3*5.00/1023$$

3. Extract and plot the altitude, column A18, in kilometers versus temperature in Kelvin.

$$Alt(km) = A18/1000$$

4. Estimate and comment on the uncertainties in your results.

5. Calculate the temperature changes as a function of altitude (the negative of the environmental lapse rate) for altitudes that are well model by straight lines.

Research the temperature data acquisition and the physics and chemistry that occur in the regions of the atmosphere examined. Answer the questions below.

Questions

1. What is a Zener diode and how can one be used to measure temperatures?

2. What do the 5.00 and the 1023 represent in the equation in Procedure 2.?

3. What is the environmental lapse rate, and why is it important?

4. At what altitude does the tropopause occur on earth?

5. What are the quantitative values for the environmental lapse rates in the troposphere, tropopause, and stratosphere?

6. What can you conclude about the presence or absence of convection in the troposphere during the ascent of the balloon flight?

7. Is cloud formation likely to be occurring at the measured tropospheric lapse rate?

8. What is the heating process that warms the stratosphere on Earth?

9. Why has ozone depletion occurred in the atmosphere? Why is ozone an important constituent of the stratosphere?

10. From the Huygen's spacecraft graph of temperature versus altitude, how does the temperature at the surface of Titan compare to the temperature at the surface of the Earth?

11. From the graph, what are the quantitative values for the lapse rates in the lower troposphere, tropopause, and lower stratosphere of Titan.

12. What can you conclude about convection in the lower troposphere of Titan from measured environmental lapse rate?

13. Between what altitudes does the tropopause occur on Titan?

14. What is the heating process that warms the stratosphere on Titan?

15. Investigate the temperature profiles of the atmospheres of Venus and Mars. What can you say about the stratospheres of these planets?

Acknowledgments

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References

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[2] http://pds-atmospheres.nmsu.edu/education_and_outreach/encyclopedia/adiabatic_lapse_rate.htm The Planetary Atmosphere Data Node [cited 23 May 2011]

[3] Lucy-Ann McFadden, Paul R. Weissman and Torrence V. Johnson, Editors, *Encyclopedia of the Solar System*, Academic Press, Boston, MA, 2007, Chapters 7, 9, 15, and 25

[4]NSF CCLI Balloon Workshop, Taylor University, 29 – 30 July, 2009, Reference documents and references therein

[5] Fulchignoni, M., et al. "In situ measurements of the physical characteristics of Titan's environment", Nature **438**, 785-791, 8 December, 2005