A Liquid-Nitrogen Cannon

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For several years now the University of Arizona Astronomy Camps[1] have used liquid nitrogen ($LN_2$) for fun and exciting demonstrations that are also thought-provoking and can be analysed quantitatively. It fascinates kids and adults and can be used to reinforce many concepts in physics, astronomy and engineering. For instance:[2]

- Observe the nitrogen in a styrofoam cup. Notice the roiling motion and the vapor that falls, unlike the vapor from boiling water.
- Pour some nitrogen out. Nitrogen drops will skitter across the floor, riding on a cushion of nitrogen vapor (Leidenfrost Effect).
- Place an inflated balloon in the nitrogen, liquifying the air inside, which is mostly nitrogen. The volume ratio of gaseous (20°C) to liquid nitrogen (77K) is 691:1; for water the ratio is 1700:1. (You can have students calculate these figures.) The balloon reinflates when you allow it to warm.
- Freeze and shatter various items, such as racquetballs, eggs, chocolate bars, flowers, etc. Use the egg to hammer a nail into wood. Note the different behaviors of the different materials. What returns to normal when warmed? How does the brittleness of certain materials at low temperatures affect the design of a probe bound for Saturn, where temperatures are about this cold?
- Liquify the air inside a soda can by flipping it top-down in $LN_2$. Atmospheric pressure crushes the can.
- Place one end of a room-temperature rubber tube into the liquid nitrogen. A geyser erupts, similar (it is thought) to how the geysers of Neptune's moon Triton work.
- Make $LN_2$ ice cream. Brew up a batch of your favorite ice cream recipe, but instead of using the standard ice-and-salt freezer, freeze the mixture by pouring liquid nitrogen directly into it while vigorously stirring. Much faster than the usual technique!
- Cool a superconductor and levitate a magnet above it, showing the Meisner effect.[3]
- Put a little $LN_2$ in a peanut can or tupperware container and put on the lid. After a short time the pressure will build and the top will pop off dramatically.
- Fill a plastic soda bottle about a third full with $LN_2$ and put the cap on. Put it in a large pot half full of warm water and run away! Even from 50 feet away the boom is impressive.

Recently, we've added a new weapon (!) to our arsenal of liquid nitrogen demos: a cannon (Figure 1) A large, metal tube serves as the barrel, a sealed plastic soda bottle one-third full of $LN_2$ is the charge, and a softball or other object serves as projectile. As the nitrogen boils, the pressure builds inside the bottle until it bursts, sending the projectile to impressive heights.

The idea for the $LN_2$ cannon, and the cannon tube itself, were donated by a Tucson-area commercial optical company. The technicians there would occasionally launch softballs during their lunch hour. Unfortunately, one day the projectile landed on the boss's car. That ended that, and the tube was given to the Astronomy Camp.

Everyone gets very excited about this, but it is important to always stress safety. When the bottle ruptures, the plastic fragments are sharp and hard shrapnel. Because of air resistance, they are not dangerous beyond twenty feet or so, but at close range are. Plus, you don't know exactly when the cannon will go off. Typically, we have a seven-minute delay between the sealing of the bottle and its bursting. This time can be shortened drastically by pouring warm water over the bottle once it is loaded in the cannon. We also have a stand made of plastic tubing (seen in Figure 1), to prevent the cannon barrel from falling over.

So far we haven't even mentioned the precautions necessary when working with the $LN_2$ itself. Boiling at a temperature of 77 Kelvin (-196 Celsius), liquid nitrogen can quickly cause severe 'burns' on the skin. Wear thick gloves with impermeable (waterproof) outer shells. Have tongs for retrieving items from the nitrogen. It is possible (and dramatic!) to pour the nitrogen over an unprotected hand or arm, but be sure it rolls off immediately. Don't pour nitrogen into a cupped palm! One risk to beware of is the nitrogen spilling onto, and soaking into, clothing — unable to flow away, it can cause burns. Wear loosely-fitted clothing.

Where can you get liquid nitrogen? If you teach at a research university, the physics, chemistry or astronomy departments should have a plentiful supply. If your institution doesn't have a supply, then you need to do some scrounging. Places to try are: nearby universities, welding supply companies, medical cryogenic supply companies. Cost is usually about a dollar per liter.

Before getting the nitrogen you must be prepared to transport and store it. Foremost, you need a large dewar (10 liters at least) for storage. Perhaps you can borrow or rent one from the place you get the nitrogen itself. If not, you'll need to buy one. A new 10-liter dewar will cost you about $300. One of us (JRR) was able to get a good 25-liter dewar from Maryland state surplus for only $20. Be sure the dewar is secured in your vehicle so it can't tip over if you stop suddenly.

You will also need smaller containers. An all-metal thermos bottle works well (whatever you do, don't seal the thermos!), but don't use a thermos with a glass interior since the glass will crack in the cold. Nested styrofoam cups work reasonably, as does a small coffee can nestled inside a large coffee can, surrounded by styrofoam peanuts.

We have actually used two versions of the cannon, shown in Figure 2. Our original cannon uses a 4.5" inner-diameter aluminum tube, which is just the right diameter for a two-liter soda bottle. The other uses a 2.5" ID steel tube, with a plastic bottled-water bottle holding the $LN_2$ charge. You will probably find it easier to scrounge the smaller-diameter steel tube. Talk to the maintenance folks at your school.

Although the gee-whiz aspect of liquid nitrogen is fun and inspirational, we have also done more detailed quantitative exercises, both at Astronomy Camp and in the high-school physics classroom. Some ideas:

- The physics of how a dewar or thermos bottle insulates so well is fascinating. Using the Stephan-Boltzmann equation, calculate the rate of heat loss due to radiation. Knowing the latent heat of vaporization (a.k.a. enthalpy of vaporization) for the nitrogen, calculate an upper limit for the "hold time" of your dewar.
- Two-liter soda bottles typically burst at pressures of 180 to 200 p.s.i.[4]. Do a theoretical calculation of the muzzle velocity of your cannon. Also try to predict how much time it will take for the bottle to burst.
- Videotape a cannon launch, trying to capture the ball in at least two frames as close to the top of the tube as possible. This can be difficult because the ball is surrounded by nitrogen gas as it exits the tube. Painting the ball fluorescent pink and/or back-lighting may help. If your videocamera has it, use the high-speed shutter setting. This will reduce the blurring of the ball's image in the individual frames (although it doesn't change the frame rate of 30 frames per second.) See Figure 3 for example.
- Determine the height of a cannon launch using metersticks with attached protractors and plumb bobs as simple transits. Use the height calculated to find a lower bound of the projectile's muzzle velocity. You can also time the flight of the projectile to determine the height and muzzle velocity.
- Compare the various muzzle velocity determinations obtained and discuss the assumptions and simplifications that affect their accuracy.
- Assuming an average density of 5 $g/cm^3$, from what size planet or asteroid (assumed spherical) could your cannon launch a projectile at escape velocity?

See Figure 3 for an example of one handout we have used to guide students. Some of the properties of liquid nitrogen you might find useful are[5]: boiling point -195.8°C; density 0.804 g/cc at the boiling point; $L_V$= 47.6 cal/g = $1.992 \times 10^5$ J/kg; vapor density at b.p. 4.613 $kg/m^3$.

We feel that the liquid-nitrogen cannon can play a part in physics courses at all levels. Its operation can be understood conceptually, it can be a topic of quantitative analysis at various levels of sophistication, and it grabs the attention of everyone!

[1]For more information on Astronomy Camps for Teens, Adults, and Teachers, call Dr. Don McCarthy at (520)621-4079, email *mccarthy@as.arizona.edu,* or visit our Web page at *http://ethel.as.arizona.edu/astro_camp.*

[2]These and other demonstrations are discussed in more detail in several past*Physics Teacher* articles. See Nov. 1990 (p.544) and November 1994 (p.508).

[3]Superconductors can be had from many science suppliers, such as Edmund Scientific, which sells them for about $20.

[4]Mr. Joe Karowski, Quality Control Manager, Conscar, Inc., Phoenix AZ. This is at room temperature and may not be accurate at 77K.

[5]CRC Handbook of Chemistry and Physics, 65th ed.

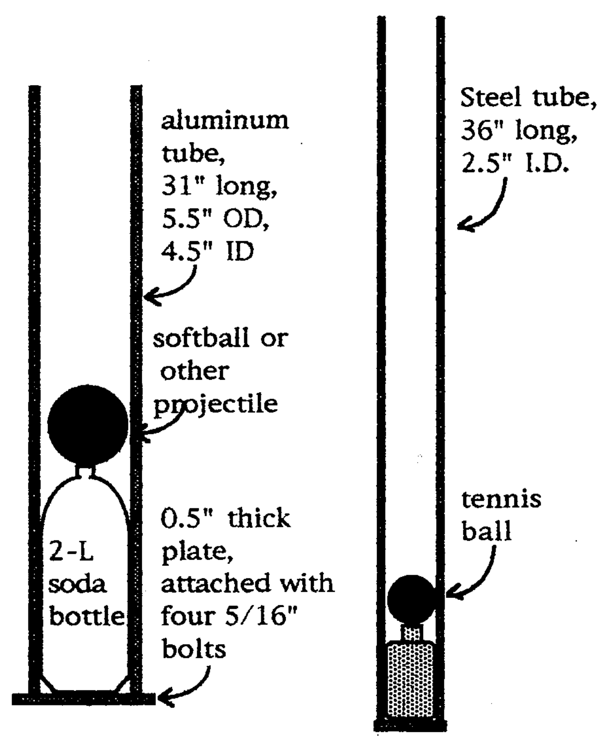
## Figure Captions

Figure 1. The cannon just after a launch (a) from a distance and (b) closeup. Note the plastic stand preventing any possibility of the cannon tipping over.

Figure 2. Dimensions of our two $LN_2$ cannons.

Figure 3. Consecutive video frames showing projectile leaving the cannon. Using the height of the cannon tube (0.914m i.e. 3 feet) as a scale, the average velocity of the projectile in this 1/30-second interval is 80 m/sec

Figure 4. One possible quantitative exercise using the liquid-nitrogen cannon.



# $LN_2$ CANNON ANALYSIS

DATA

mass of projectile (in kg): m=

diameter of tube (in m): d=

time of flight (in sec): $t_{total}$=

angle of apogee ______° viewed from ______ m from launcher.

depth of projectile in tube (in m): $d_{tube}$=

cross-sectional area (in $m^2$): A=

ANALYSIS

Using the time of flight information, calculate the apogee height of the projectile, $h_{max}$.

Using the angle of apogee information and trig, again calculate the apogee height of the projectile, $h_{max}$.

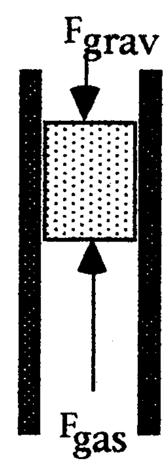
Ideally, your two determinations of $h_{max}$ should be very close. Are they? If not, why not?

Energy is conserved except that air resistance may 'steal' some energy and convert it to heat. Let's ignore that for the moment. Therefore, $PE_{apogee} = KE_{i,\min}$. Using this, your data and $h_{max}$, calculate the minimum speed the projectile had, when it left the tube, $v_{i,min}$.

Assume uniform (constant) acceleration inside the tube. The equation for this is $a = \frac{v_{i,\min}^2}{2d_{tube}}$.

Calculate the acceleration.

What net force is necessary to produce that acceleration?




What is the force provided by the gas pushing on the projectile?

Pressure is P=F/A. What is the gas pressure behind the projectile?

In order to escape a planet's gravity, a projectile must reach a speed of

$$v_{esc} = \sqrt{\frac{2Gm_{planet}}{r}}$$ (For Earth, this is about 11000 m/sec.)

Solve this equation for $m_{planet}$.

Now, let's calculate how small a planet must be for this cannon to be able to put the projectile into orbit...

In general, the mass of an object is equal to its density times volume: $m = \rho V$.

Let's assume our small planet is spherical; the volume of a sphere is $V_{sphere} = \frac{4}{3}\pi r^3$,

So the mass of a planet is $m_{planet} = \frac{4}{3}\pi r_{planet}^3 \rho$

Plug this into the equation for escape speed. This eliminates $m_{planet}$ from the equation in favor of the density. We do this because we don't know the mass of the planet, but the density of rock is typically about 3000 kg/$m^3$.

Solve your equation for r. Plug in 3000 kg/$m^3$ for the density and our calculated projectile speed for $v_{esc}$ to find the maximum radius of a rocky planet from which the cannon could launch a projectile with enough speed to escape.