What is the Age of the Milky Way?

Teacher Guide

Introduction

A white dwarf is the final stage in the life of a star like the Sun. During this phase of a star's life, the star's hot core collapses, which makes it even hotter. At the same time, the star ejects its outer layers. What remains is a hot dense Earth-size ball about half the mass of the Sun – a white dwarf. A white dwarf cools down by radiating light. It shines by the energy left over from its core as a star and its collapse. Knowing how the white dwarf's temperature changes with time (cooling), astronomers can deduce the age of the white dwarf. By observing lots of white dwarfs and calculating their temperatures, astronomers can estimate the age of the Galaxy.

Currently, Dr. Ted von Hippel and his national collaborative team are performing a survey of stars. In a way, they are sifting out the white dwarfs from the thousands of other stars. They use Sloan Digital Sky Survey observations to identify thousands of white dwarfs candidates to increase their sample size of white dwarfs to the current number (as of 2004) of about 400. As the number of white dwarfs in the sample increases, the precision of their age of the Galaxy estimate gets better.

Materials

For each cooperative group	For the class
Three 16 oz Styrofoam cups	Pyrex measuring cup
Thermometer capable of 20^o – 100^o C	Marking pen
Digital thermometers work very well.	Source of boiling water: electric kettle.
Clock or stopwatch	Permanent markers (variety of colors)
Transparency film	
Graph paper	
Pencil	

NSES

Grades 9 – 12 Physical Science: conservation of energy and the increase in disorder.

TEKS

112.47 Physics

7. The student knows the laws of thermodynamics.
   - A. analyze and explain everyday examples that illustrate the laws of thermodyanamics.
   - B. evaluate different methods of heat transfer that result in increasing amounts of disorder.

Student objectives:

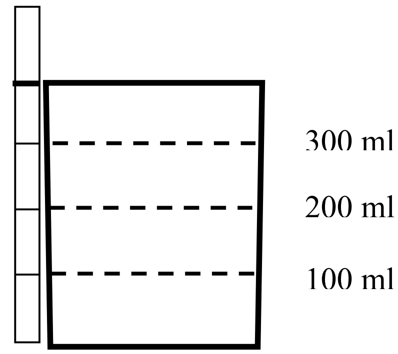
- ⋆ Measure the changing temperature of water (100, 200, or 300 ml) as it cools from 100^o C.
- ⋆ Plot temperature vs. time data to make a cooling curve.
- ⋆ Compare and contrast cooling curves for different amounts of water.
- ⋆ Fit white dwarf temperatures to a model white dwarf cooling curve.
- ⋆ Estimate the age of our galaxy based on the coolest white dwarfs observed.

Preparation

Preparation Time: 20 minutes

1. Mark a cup

Fill a cup with 100 ml of *cool* water, and mark the level with a pen around the outside of the cup. Repeat for 200 ml and 300 ml of water. Shining a flashlight through the Styrofoam cup clearly shows the water level.



2. Transfer the marks on the cup to a straw.

You will use this straw as a reference for pouring boiling water into each group's cup, and the mystery cups.

Each group will investigate one cup of hot water either 100, 200, or 300 ml. More than one group may investigate the same volume of water.

3. Divide the white dwarf temperature data into parts for the groups.

Each group should have at least five stars of different temperature with a total of at least forty stars plotted by the class as a whole. (See the Explore section). This unit provides data from a scientific publication (with information extraneous to this exercise) and a shortened data sheet with abridged data for the exercise. You may choose which data sheet to share with your students. If you use the long list, make sure that stars cover a range from very hot (20,000 to 10,000 Kelvin) to the cool (5,000 to 3,000 Kelvin).

4. Prepare the mystery cups.

While students are busy recording water temperature (Explore section), you will fill three cups (100, 200, and 300 ml) with boiling water, but at *different times.* Note the time you add the water for each cup. Later on, students will estimate when you added the boiling water to the cups based on their data and the current temperature of the water (Explore section). Select a place away from (but in view of) the students' work area to set up the mystery cups so that students can't easily tell what you are doing.

5. Just before class begins, pour one liter of boiling water into a Pyrex beaker.

Set a thermometer in the water so that it does not touch any part of the beaker, write down the initial temperature, then begin a stopwatch. (See Engage step #1)

- To keep the tip of the thermometer immersed in the water without touching the cup, try clipping a binder clip to the side of the cup. Slide the thermometer stick through one handle of the clip so that the clip holds the thermometer and suspends the tip inside the cup. Use this same technique with the students' styrofoam cups.

6. Set out the materials on a central table.

Students:

1. Divide students into cooperative lab groups.

2. Assign responsibilities to group members: materials manager, timer, data recorder, data plotter.

Activity

Engage (15 minutes)

1. Fill a Pyrex beaker with boiling water, and place a thermometer into it. Write down the initial temperature and start a stopwatch to keep the time that the water is cooling. Leave the running stopwatch beside the beaker of hot water.
Extension: You may use a Calculator Based Laboratory (CBL) temperature probe and calculator to automatically record the temperature and generate a plot.

Whole class participation

2. Tell students what the initial temperature of the water was, and then the present temperature and time elapsed. Ask students how long they think the water will take to cool down to:

- 10^{o} C below the present temperature
- 15^{o} C below present temperature
- 20^{o} C below present temperature
- room temperature (about 21^{o} C)

3. Accept all answers. Write down students' estimates on the board, overhead, or computer and video projector. Plot their estimate on a graph.

4. Ask students for other examples of cooling over time: car engine, oven, curling iron, clothes iron, pizza, charcoal or gas grill, or a cup of hot cocoa. Some may even mention dead bodies. List these items on the board or overhead projector.

5. Tell students that this cooling beaker of water is a like a white dwarf. The water and the white dwarf cool down over time.

6. Break students into their cooperative lab groups. Assign a materials manager to collect the materials.

7. At the end of class, check the water temperature and time. How much did it cool? Compare the students' initial estimate and graphs in item (2) to their graphs of cooling water (see the Explore and Explain sections).
Extension: Show students the data and the plot from the CBL if you have used it.

Explore: How fast does water cool? (60 minutes)

Measure the changing temperature of the water (20 minutes)

1. Assign each lab group one of the three volumes of water to investigate: 100, 200, or 300 ml.

2. Review safety procedures with students. Warn them that they will be working with hot water that could burn their skin.

3. Review the lab objectives with students.

4. Students can use their data table "How Fast Does the Water Cool?" and graph to record and plot their temperature data.

- If you choose to use Excel for data entry and plotting, the Excel graphic wizard can set the x- and y-axis scales automatically. Emphasize to students that they should critically evaluate the axis scale, and experiment with the gridlines and axis scale settings for the best representation for their data.
- Be sure that all groups use the *same x-and y-axis scale.* Explain that if each group uses different scales, students will have difficultly comparing their results.

5. The materials managers should collect materials and a cup. Each group should be ready to do their observations, and have the thermometer inside the cup.
Note: the thermometers should not touch the bottom of the cup. For best results, the tip of the thermometer should lie immersed in water without touching the cup. If the tip touches the cup, the cup will insulate the tip from the water. The resulting plots will not show the characteristic cooling curve shape.

6. Go to each group and carefully pour the boiling water into the cups. Use your straw marked with the 100, 200, and 300 ml levels as a guide. Once you pour the water, students should record the initial temperature, then begin their observations. The initial temperature should be at least 95^{o} C.

7. Student observations: measure the temperature of the water over a 10-minute time interval.
    1. Record the initial temperature of the water, then begin the stopwatch.
    2. Record the temperature of the water At 20-second intervals.
    3. Plot the temperature vs. time on the graph paper.
    4. Record the final temperature after 10 minutes have elapsed.

8. While students are measuring the temperature of their water, pour boiling water into the three mystery cups (100, 200, and 300 ml) you prepared earlier away from view. Vary the time that you add the water to each mystery cup by about two minutes per cup. For each cup, record (for yourself) the time that you added the water.

9. Tell students that each group will present their cooling curve to the rest of the class. Ask students to list questions they should think about as each group presents their curve. For instance:

- What is the cooling rate?
- Is the cooling rate constant or does it change over time?
- When did the water cool the fastest?
- When did the water cool the slowest?
- Does the amount of water change the cooling rate?

When was the water poured into the mystery cups? (10 minutes)
1. Tell students that you have poured boiling water into three cups at either 100, 200, or 300 ml., each with a thermometer. Ask them to predict when you added the boiling water to the cups. Students should use their cooling curves to estimate how long the water has been in the cups.

> Note: If the temperature of the mystery water is too low (off students' 10 – minute cooling curves) then they must decide how best to make an estimate. If they find an average cooling rate using *all* their data points, their estimate will too short. They should use the last 5 to 10 data points (where the cooling rate is slowest) to make an estimate.

2. Compare the results. The precision and accuracy of the estimates should decrease as the temperature of the water decreases. As the cooling rate slows down, students will find it difficult to match up a temperature and time. The same is true for astronomers trying to determine the age of a cool white dwarf.

Group presentations (15 minutes)
Compare cooling curves across groups. Lay the curves down side by side for easy comparison. As each group discusses their curve, other students should listen and try to answer their questions from item seven of the Explore section.

> Note: If students use Excel to make their plots, make sure that each lab group uses the *same axis scale settings* as the others. Otherwise, students will not be able to easily compare their results because each group will probably use a different scale. Excel can automatically set the scale, but the settings will not be consistent between groups.

Whole class participation (10 minutes)
1. Ask students to list methods of heat energy transport:
- Conduction: water molecules "kick" the Styrofoam cup and air molecules.
- Convection: cool water sinks, hotter water rises in the cup.
- Radiation: the hot water radiates infrared light.

2. Ask students to identify the main variables in their experiment, and explain their significance.
- water temperature: students measured the water temperature using a thermometer. The temperature is related to the kinetic energy of the water molecules (see *A Word from the Astronomer* regarding temperature).
- time: students measured time in seconds and minutes in order to determine the rate of change of the temperature for the water.
- initial water temperature (slightly different for each group):
- volume of water (three different volumes):
- surface area of the water: the water touches the cup and air. The surface area is different for each volume and affects the heat transfer rate.
- surface area to volume ratio: If this ratio is very high, the water has a large area for heat transfer and so will cool quickly. For instance, if you poured the boiling water on the floor, the water would spread out and contact the cool floor and air. In a few seconds, the water would cool from boiling to about the floor temperature.

Investigating models of white dwarf cooling (15 minutes)

1. Ask students to predict the cooling curve for one liter of water with an initial temperature of 100^{o} C. In what ways will it be different from the water samples they measured?

2. Show students the cooling curve for one liter of water. Compare the one liter of water cooling curve and the curve students just plotted from their own water sample.

- The rate of change in temperature over time is slower. This rate is the slope of the curve at any point.

3. Tell students to examine the cooling curves for a deceased human body, stovetop skillet, oven, and car engine. What are the similarities and differences?

4. Tell students to examine the cooling curve of the white dwarf. Compare the white dwarf cooling curve to the other cooling curves.

> Note: This is a computer generated model of a 0.6 solar mass white dwarf cooling curve. Astronomers have observed hundreds of white dwarfs. The average white dwarf mass is about 0.6 solar masses. Some are more massive, like Sirius B (1.1 solar masses), and others are less massive (down to about 0.2 solar mass).

5. Pass out, a sheet of transparency film and a colored permanent marker (different colors to each group if possible). Tell students to trace the axis of the plot onto the transparency film.

6. Assign each group a small set of white dwarfs to plot from your prepared tables.

5. Ask each group to plot their portion of white dwarf data on the transparency film with white dwarf cooling curve as a guide. Students should find the temperature of each white dwarf on the curve, then mark it with the pen.

6. Collect the transparency film from each group. Stack the film on top of the white dwarf cooling curve transparency. Show the superimposed plots to students.

What do the table headings mean?

Catalog Name: This is position of the white dwarf in the sky, which is unique. The first set of numbers is the right ascension (RA) in hours, minutes, and seconds. The second set is the declination (Dec) in degrees, minutes, and seconds. Declination is the angular position north or south of the celestial equator. RA is how far the white dwarf is east of the vernal equinox, where the celestial equator and ecliptic intersect.

Type: Astronomers classify white dwarfs (spectral type D for dwarf) according to their spectral properties. The spectral features in the white dwarf spectrum are broad, spread out by gas at extremely high density.

DA – thin hydrogen atmosphere. Its spectrum looks like an A-type star, which shows strong hydrogen absorption features.
DAH –
DA+M - a binary star system with a DA type white dwarf and M type star.
DB – helium atmosphere, showing only helium absorption features in its spectrum.
DC – shows no absorption features in its spectrum.
DZA – shows hydrogen (H) strongly, ionized calcium (Ca), magnesium (Mg), iron (Fe), and sometimes sodium (Na). The "Z" means atoms with an atomic number greater than 3.

Effective Temperature (T_{eff}): The temperature of a blackbody that matches the spectral energy distribution of the white dwarf or star. For instance, if you measured how much energy the Sun radiates at each wavelength and plotted it (energy vs. wavelength) you would see a curve that looks much like a blackbody curve. A blackbody with a temperature of about 5,770 Kelvin would closely resemble the Sun's energy vs. wavelength curve.

Bolometric Magnitude (M_{bol}): The Sun, other stars, and white dwarfs radiate light across the entire electromagnetic spectrum. The absolute bolometric magnitude is how bright the star would appear if it were located 10 parsecs (32.6 light-years) away. It includes all the light the star radiates across the entire electromagnetic spectrum. Our atmosphere blocks light in many regions in the spectrum, and light detectors are sensitive in only small regions of the spectrum. If a light detector is sensitive to only the visible spectrum, it will miss light of shorter wavelengths and longer wavelengths. So, the brightness calculated using this detector will be less than the star's actual brightness.

Explain (20 minutes)

1.Ask student to compare their water cooling curve to the white dwarf cooling curve.
- ⋆ For both, the cooling rate slows down as the temperature decreases.

2. Tell students to examine the plot of the white dwarfs.
   a. Where are most of the white dwarfs located on the combined plot?
   b. Where are the oldest white dwarfs?
      - o These are the coolest white dwarfs. Notice that that there seems to be limit on the cool end of the temperature scale.

3. Ask students to explain which white dwarfs are the brightest, based on their experiment.
- The hotter the white dwarf, the more light it radiates. A white dwarf radiates energy like a blackbody, that is the luminosity is proportional its temperature raised to the **fourth** power.
- When the water temperature was high, near 100^{o} C, it felt hot. Heat, or energy transfer from hot to cool objects, was high when the temperature of the water was high.
- Students experience this as feeling hot. They measured the rate that the water cooled. The rate of water temperature change is related to heat – how fast energy transfers from the hot water to the cool air.

4. Ask students how fast they think the luminosity of the white dwarf changes compared to the temperature. Let them calculate two luminosity ratios for a 0.6 solar mass white dwarf:

$$L = 4\pi r^2 \times \sigma T^4$$

	Luminosity Ratio	Temperature Ratio
$T_1 = 20{,}000$ $T_2 = 10{,}000$	16	2
$T_1 = 20{,}000$ $T_2 = 4{,}000$	625	5

For simplicity, assume that the radius of the white dwarf remains constant as it cools. So the ratio of luminosities is the ratio of temperatures to the fourth power.

$$\frac{L_{20000}}{L_{10000}} = \left[\frac{20000}{10000}\right]^4 = 2^4 = 16$$

$$\frac{L_{20000}}{L_{4000}} = \left[\frac{20000}{4000}\right]^4 = 5^4 = 625$$

5. What could explain the cool white dwarf drop-off (Note that beyond 3,600 Kelvin, there are no more white dwarfs.)? Accept all answers. List them on the board/overhead. If students do not mention them, list these possibilities:
- Our telescopes can't detect cooler white dwarfs because they are too dim.
- Cooler white dwarfs do not exist in our sample.

6. Ask students: if we assume that our telescopes are not the limiting factor, so that we actually can see white dwarfs beyond the drop-off, what conclusions can we draw from this data about the age of our galaxy?
- The coolest white dwarfs represent the oldest stellar remnants in our galaxy.

Elaborate: Improving the Calculation for the Age of our Galaxy (20 to 40 minutes)

Tell students that they are astronomers who want to improve the calculations for the age of our galaxy based on white dwarf stars. Their objectives are:

- List simple and straightforward ideas to improve the accuracy and precision of the calculation.
- Evaluate each recommendation.
- Prioritize each recommendation.
- Present their ideas with the rest of the class.
- Evaluate the ideas other groups present.

Cooperative group work

1. Break students up into their cooperative groups. Give them a specific amount of time to brainstorm a list of recommendations. Walk about the room and assist students with their brainstorming.

2. Once students finish brainstorming, give them a specific amount of time to evaluate and prioritize their ideas.

Group presentations

Ask each group to present their ideas to the class. List the ideas on the board, overhead, or computer and video projector.

Whole class participation

Read the explanation from astronomers about what they are doing to improve their calculations for the age of our galaxy. Check off the ideas from students that match up or are closely related to what astronomers are doing.

What are astronomers doing to improve their estimates for the age of the galaxy?

Astronomers (as of 2004) have observed and determined the basic properties of about 400 white dwarfs. That may seem like a lot, but consider that most stars (0.5 to 8 solar masses) become white dwarfs. Our galaxy right now contains at least 100 billion stars, and is about 10 billion years old. Since the formation of our galaxy, lots of stars have become white dwarfs in our part of the Galactic neighborhood – certainly more than 400. An easy way to improve the age estimate of our Galaxy is to find more white dwarfs, especially the coolest and oldest ones. But that is easier said than done.

One of the main challenges is filtering out the white dwarfs from the other stars that astronomers can see. The intrinsic faintness of a white dwarf poses another challenge. White dwarfs are small, about Earth size, and so have little surface area to emit light. As a result, they are dim and difficult to detect far away. Furthermore, the coolest and oldest white dwarfs are also the faintest.

The White Dwarf and Age of the Galaxy project

Dr. Ted von Hippel has proposed a plan that involves a large team of astronomers and several instruments. The key ongoing project that makes this search for white dwarfs possible is the Sloan Digital Sky Survey (www.sdss.org), or SDSS.

Catch the stars:

The SDSS uses a 2.5-meter size telescope and an innovative wide field camera to systematically scan and map one-fourth the whole sky. The telescope is located in New Mexico at Apache Point Observatory. As of December of 2004, the Sloan Digital Sky Survey has imaged 97 percent of its baseline goal of 8452 square degrees, or 8216 square degrees of the sky. The whole sky is 41,253 square degrees (see Phil Plait's Bad Astronomy website http://www.badastronomy.com/bitesize/bigsky.html).

Find the white dwarfs:

Somehow, astronomers must pick the white dwarfs out from among all the stars imaged by the SDSS. On average, von Hippel and his team will find 8 white dwarfs for each square degree of sky. For comparison, the full Moon is 1/2 of a degree across. A square degree is about four full Moons arranged in a square. But those 8 white dwarfs are somewhere in a crowd of 1,300 to 4,500 stars inside that square degree. To sort out this handful of white dwarf candidates for detailed spectroscopic follow up, the astronomers will look for stars with apparently fast motion on the sky. Dim and apparently fast moving star must be close by. The set of nearby, dim stars will most likely contain a few white dwarfs. Astronomers will observe these stars with large telescopes equiped with a spectrograph in order to observe their spectra. Since white dwarfs have a spectrum that is significantly different from other dim nearby regular stars, they are easy to pick out from the other stars in this group.

Verify the white dwarfs and determine their temperatures:

Astronomers will verify the white dwarf candidates using huge telescopes and spectrographs to observe their spectra. These telescopes are the Hobby-Eberly Telescope at McDonald Observatory and the 6.5-meter telescope at Fred Lawrence Whipple Observatory. White dwarfs show unique spectra features that astronomers will use as input for a computer model. The model will calculate some of the physical properties of the white dwarfs, including an effective temperature and mass.

Fred Lawrence Whipple Observatory 6.5-meter telescope (http://www.mmto.org/)
McDonald Observatory Hobby-Eberly Telescope
(http://mcdonaldobservatory.org), (http://www.as.utexas.edu/mcdonald/het/het.html)

To keep up with what astronomers are doing at McDonald Observatory, visit the *What Are Astronomers Doing?* website (http://mcdonaldobservatory.org/research/).

Science Background from the Astronomers:

Astronomer Ted von Hippel answers the questions:

What is temperature?

When we mention the temperature of a material we are trying to provide one number for the entire range of internal motion of all the atoms and molecules of that material. The motion of the atoms and molecules is a form of kinetic energy, so it is no wonder that greater particle motion means more internal energy and this in turn means a higher temperature. Yet each atom or molecule has its own velocity and that velocity changes constantly as atoms or molecules bounce off one another. How is it that this complex ensemble of motions can be accurately characterized by just a single number? It turns out that even though individual atoms or molecules have their own velocities and kinetic energies, under many circumstances the distribution of all the kinetic energies of the atoms or molecules behave in a standard statistical manner, often called the Maxwell- Boltzmann distribution. Under these circumstances one number can describe the entire distribution of particle energies.

But are there cases where one number doesn't suffice? Yes, and this is often the case in nature. For instance, the Earth's atmosphere has many sources of heating and cooling, and this is a function of location over the Earth's surface, height above the ground, and time of day. The atmosphere responds by mixing, but it never reaches a uniform temperature. When you look at the atmosphere, you see the effects of scattered sunlight over a great distance, and the air you see has a range of temperatures. Likewise, when you look at the surface of a star, the surface is located at different heights as seen at different wavelengths. If you use an infrared instrument, for instance, you will see to a depth in the star's atmosphere where material has the characteristic temperature of infrared light, and this is in a cooler (generally upper) region of the atmosphere than the surface seen in optical light.

Temperature is different from the concept of heat. Heat is a measurement of the transfer of energy between a region of high temperature and a region of low temperature. Heat and work are similar concepts. Both are processes that change the internal energy of a system. So if you wanted to raise the temperature of the water inside a swimming pool by one degree Celsius, you would need to do a lot work on that system. There are lots of water molecules to speed up. However, the cup of water requires far less work to raise its internal energy so that the most probable speed of its molecules increased enough to raise the temperature by one degree Celsius.

What is the difference between direct and indirect measurements?

Direct measurements are those that one can make without any assumptions, e.g. measuring distance with a ruler. Indirect measurements are those measurements that rely on assumptions, e.g. measuring the age of a tree by counting its rings or measuring the distance to another galaxy via the brightness of its Cepheid variable stars. In reality, almost every measurement one can make requires assumptions, and there is thus a continuum between direct measurement and highly indirect measurement. They key to keep in mind when making measurements and publishing them, is what assumptions went in to converting the actual quantity you measured (e.g. counting dark and light bands in a tree you cut down) into the quantity you infer (here, age of the tree).

How do you measure the temperature of a white dwarf?

Astronomers calculate the temperature of a white dwarf star – an indirect measurement. Unlike a cup of water, or a hot oven, astronomers can not touch a white dwarf with a thermometer. But we can collect the light that the white dwarf emits using our telescopes and analyze the light with our instruments, specifically a spectrograph.

The spectrograph can spread the light out by its color or wavelength. Super sensitive CCD chips, like in a digital camera, record the intensity of the light in the spectrum from a wavelength of 400 nm (violet) to beyond 700 nm (red). We reduce and analyze the digital image of the white dwarf spectrum using a computer. The spectrum we make looks like a graph: it's a plot of the intensity of the light vs. its wavelength.

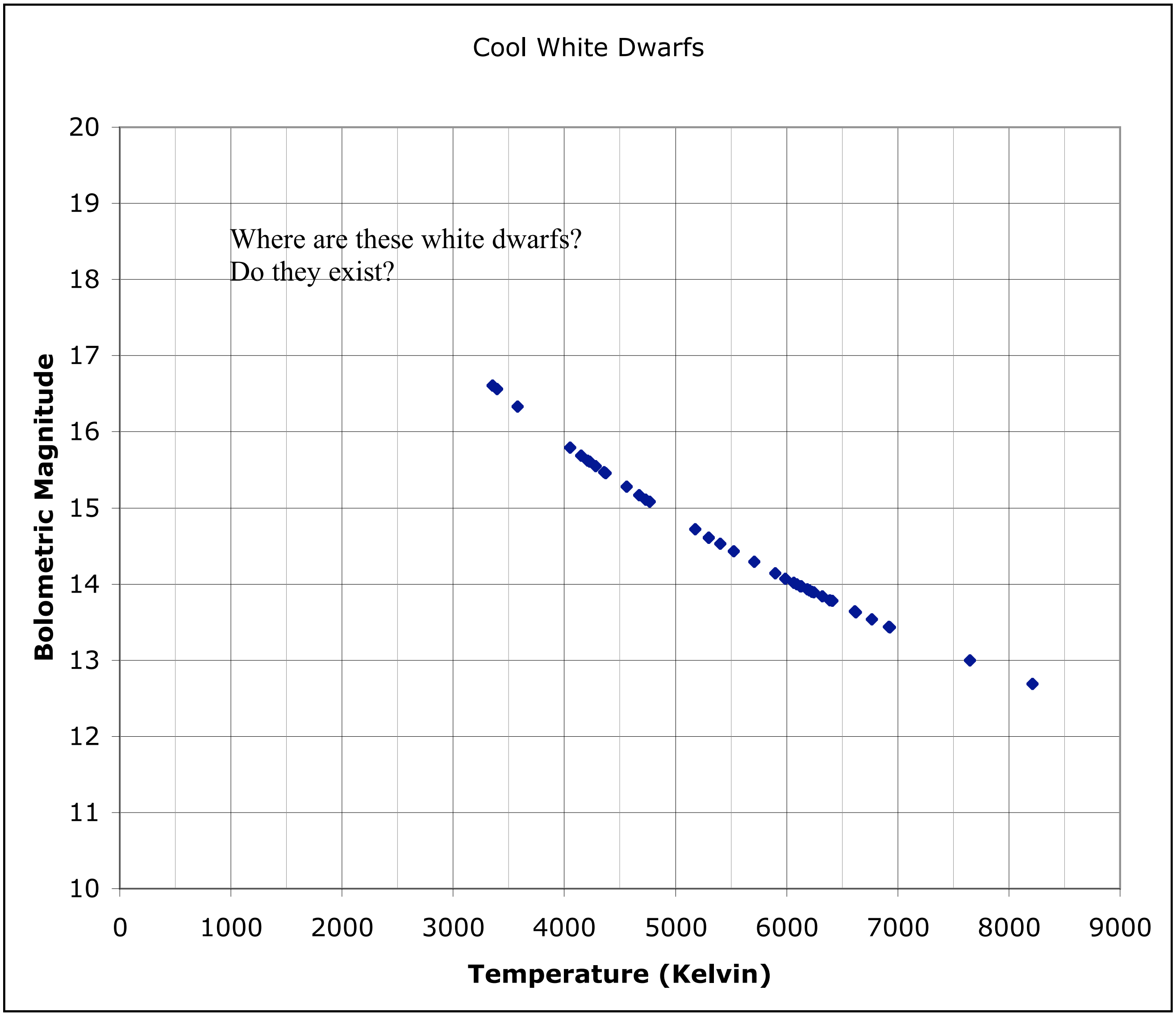
Inside the spectrum are features that tell us what elements are present in the atmosphere of the white dwarf. For instance, we can see light that hydrogen and helium has absorbed or emitted. The coolest white dwarfs show no features of hydrogen or helium. But since they are so cool, molecules can absorb some light, which leaves a set of dim absorption features at specific wavelengths. In order to estimate a temperature based on these clues, we use a computer to make a model white dwarf based on our physical understanding of white dwarf stars. The computer model can produce a comparison spectra for a white dwarf at a temperature we select. We adjust the model white dwarf temperature until the model spectrum matches the observed white dwarf spectrum. In order to make the best estimate, we use spectra collected by many different telescopes and instruments. We even use spectra in the infrared region of the electromagnetic spectrum to check our temperature estimates.

Data from Table 1 in Kilic, Mukremin, et al. *Cool White Dwarfs in the Sloan Digital Sky Survey* 2005.

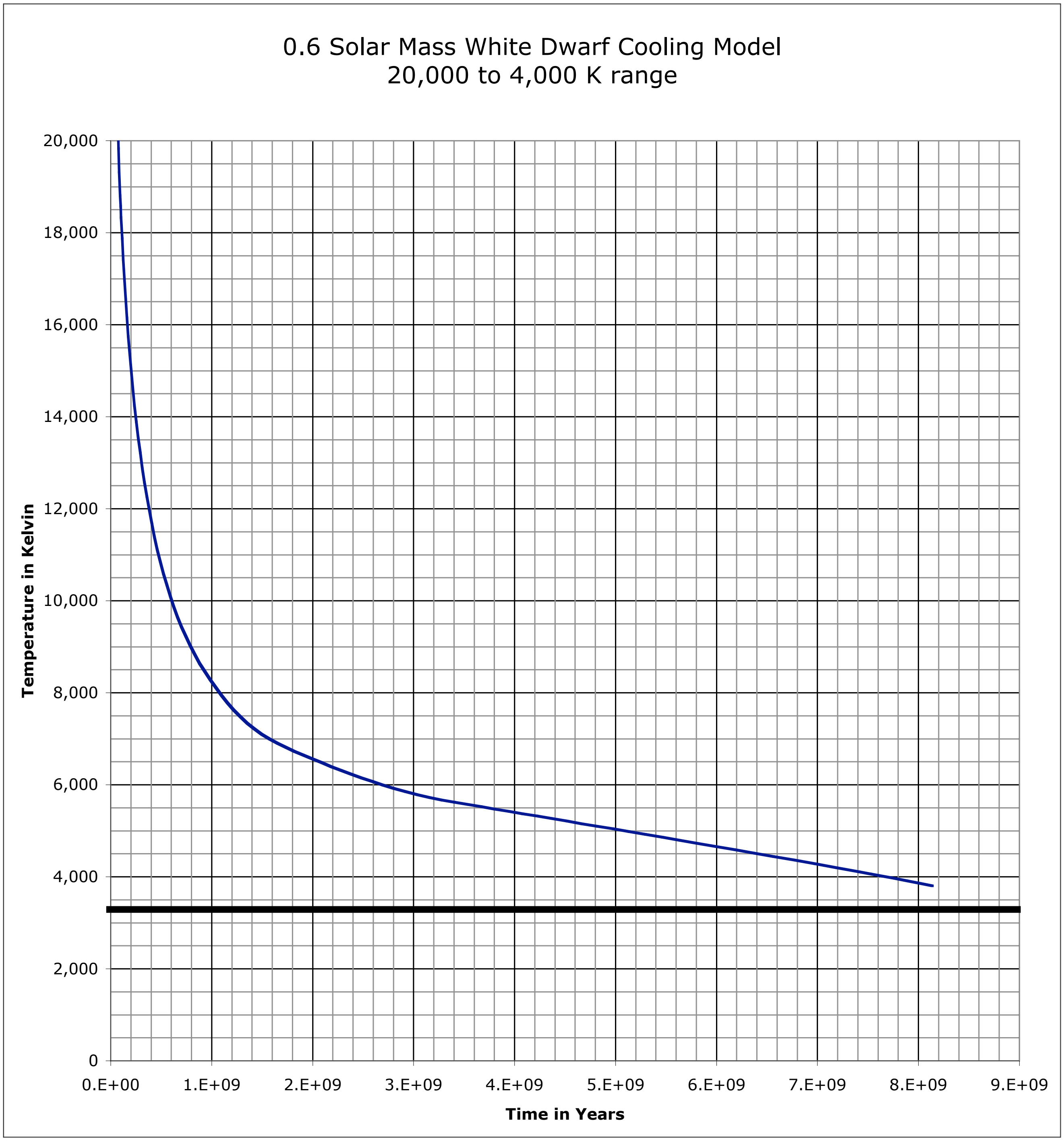
Catalog Name	Name	Type	Effective Temperature	Bolometric Magnitude
00 11 42.6 -09 03 24.3	WD 1	DA	6125	13.97
00 45 21.88 +14 20 45.3	WD 2	DZA	4732	15.11
01 15 14.73 +14 35 57.5	WD 3	DA	6320	13.84
01 59 38.43 -08 12 42.4	WD 4	DA	8214	12.69
02 56 41.62 -07 00 33.8	WD 5	DC	4211	15.62
03 14 49.81 -01 05 19.3	WD 6	DA	5709	14.29
04 06 32.39 -04 32 50.4	WD 7	DA	6624	13.63
07 53 13.28 +42 30 01.6	WD 8	DC	4226	15.61
08 20 56.07 +48 03 52.9	WD 9	DA	6388	13.79
08 36 41.36 +45 56 58.7	WD 10	DC	4373	15.46
09 19 48.92 +01 15 53.0	WD 11	DA	6227	13.9
09 42 44.94 +44 37 43.1	WD 12	DC	4052	15.79
10 02 25.85 +61 08 58.1	WD 13	DC	3581	16.33
10 11 05.63 +00 29 44.4	WD 14	DAH	6184	13.93
10 23 56.10 +63 48 33.8	WD 15	DA	6243	13.89
11 11 54.54 +03 27 26.2	WD 16	DA	5899	14.14
11 19 40.62 -01 07 55.1	WD 17	DC	4283	15.55
11 44 39.54 +66 29 28.5	WD 18	DAH	6919	13.44
12 02 00.48 -03 13 47.4	WD 19	DC	4151	15.69
12 05 29.15 +04 49 35.6	WD 20	DC	5524	14.43
12 34 08.12 +01 09 47.4	WD 21	DA	5177	14.72
13 00 21.25 +01 30 45.5	WD 22	DA	5297	14.61
12 13 13.12 +02 26 45.8	WD 23	DC	3394	16.56
13 39 39.55 +67 04 49.8	WD 24	DA	6409	13.78
14 26 59.40 +49 21 00.6	WD 25	DC	6927	13.43
15 55 34.18 +50 25 47.8	WD 26	DA	6204	13.92
16 23 24.05 +34 36 47.7	WD 27	DA	7650	13
16 48 47.07 +39 39 17.0	WD 28	DC	5401	14.53
17 04 47.70 +36 08 47.4	WD 29	DC	4560	15.28
17 24 13.32 +27 56 55.2	WD 30	DA	6131	13.97
20 41 28.99 +00 37 34.4	WD 31	DA	4673	15.17
20 45 06.97 +00 37 34.4	WD 32	DA	6093	14
21 16 40.30 -07 24 52.7	WD 33	DC	4359	15.47
21 25 01.48 -07 34 56.0	WD34	DA	6063	14.02
21 54 30.69 +13 00 26.7	WD 35	DZA	4768	15.08
22 41 57.63 +13 32 38.8	WD 36	DA	5986	14.07
22 54 08.64 +13 23 57.2	WD 37	DC	3356	16.61
23 30 40.47 +01 00 47.4	WD 38	DA	6768	13.54
23 40 41.47 -11 06 36.9	WD 39	DA+M	6612	13.64
23 54 16.59 +00 30 01.2	WD 40	DA	5298	14.61

Legend for White Dwarf Spectral Types: These are classifications of white dwarfs based on their spectra.

DA	thin hydrogen atmosphere. Its spectrum looks like an A-type star, which shows strong hydrogen absorption features.
DAH	
DA+M	a binary star system with a DA type white dwarf and M type star.
DB	helium atmosphere, showing only helium absorption features in its spectrum.
DC	shows no absorption features in its spectrum.
DZA	shows hydrogen (H) strongly, ionized calcium (Ca), magnesium (Mg), iron (Fe), and sometimes sodium (Na).



Note: the greater the bolometric magnitude, the less light the white dwarf emits. In this sample of white dwarfs, none exist cooler than 3,356 K. White dwarfs hotter than 9,000 K exist, but they are not included in this sample of the cool white dwarfs.



Note: 1.E+09 is 10^9 or one billion (1,000,000,000) years. The heavy black line is 3,394 Kelvin.

Appendix

Making the Cooling Curves

The author measured the cooling rates for 1 Liter of water, oven, skillet, and car engine using the same type of equipment students use to measure the cooling rate of water in this activity. In each case, the tip of the digital thermometer was in direct contact or completely immersed in the cooling matter. Since the cooling rate is proportional to temperature (hot water temperature changes faster than warm water temperature), the author frequently measured the temperature of each object within the initial few minutes of cooling.

1 Liter of water

Materials

4-Liter stock pot, stove, 2-Liters of tap water, Pyrex 1-Liter measuring bowl, digital thermometer, binder clip, cotton towel, clock.

Procedure

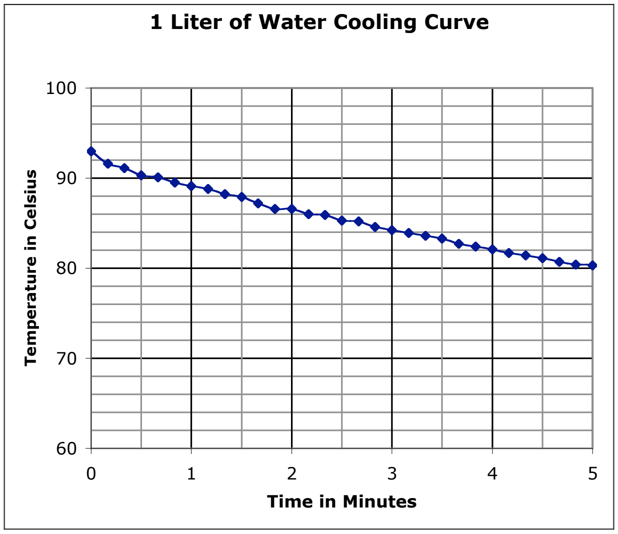
2-Liters of water was boiled in a 4-Liter stock pot. Once the water boiled, the entire 1-Liter Pyrex measuring bowl was immersed in the boiling water, then removed and set on the counter top, with a cotton towel between the bowl and countertop. About 700 ml of water remained in the bowl. After inserting the thermometer, then topping off the measuring bowl to one Liter of water, the initial temperature was recorded. During the first five minutes, temperature measurements were taken every 20 seconds. The total time interval for measuring temperatures was 71 minutes.

After several unsuccessful trials, the author settled on the above method for measuring the cooling rate of water that minimized confounding variables:

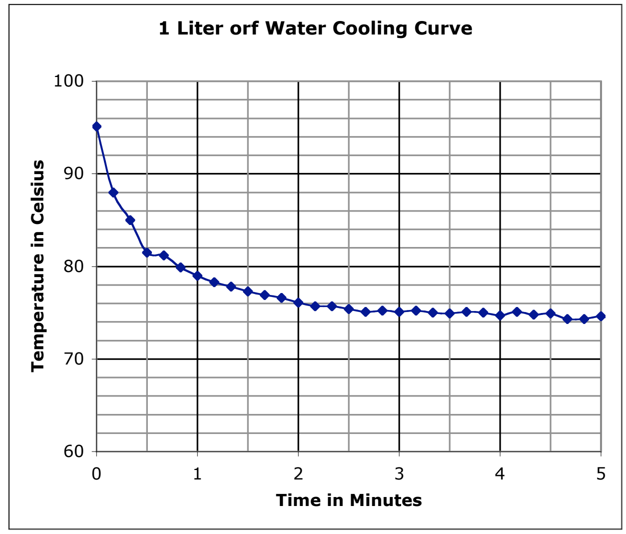
1. Temperature of the Pyrex measuring bowl: During the initial trials, the Pyrex bowl was not heated. Boiling water was poured into the bowl, with the bowl at room temperature (21^{o} C). So the system of the bowl plus the water was not the same temperature.
2. Thermometer tip contact with the Pyrex bowl: When the thermometer tip was in contact with the Pyrex bowl, it measured the temperature of the bowl and water. The author clipped a medium size binder clip to the side of the bowl to hold the thermometer tip inside the water without touching the bowl.
3. Heating the countertop: Initially, there was no insulation between he counter top and Pyrex bowl. The cotton towel insulated the bowl from the cool countertop.

Below is a cooling curve over 5 minutes from the initial trials verses the final cooling curve:

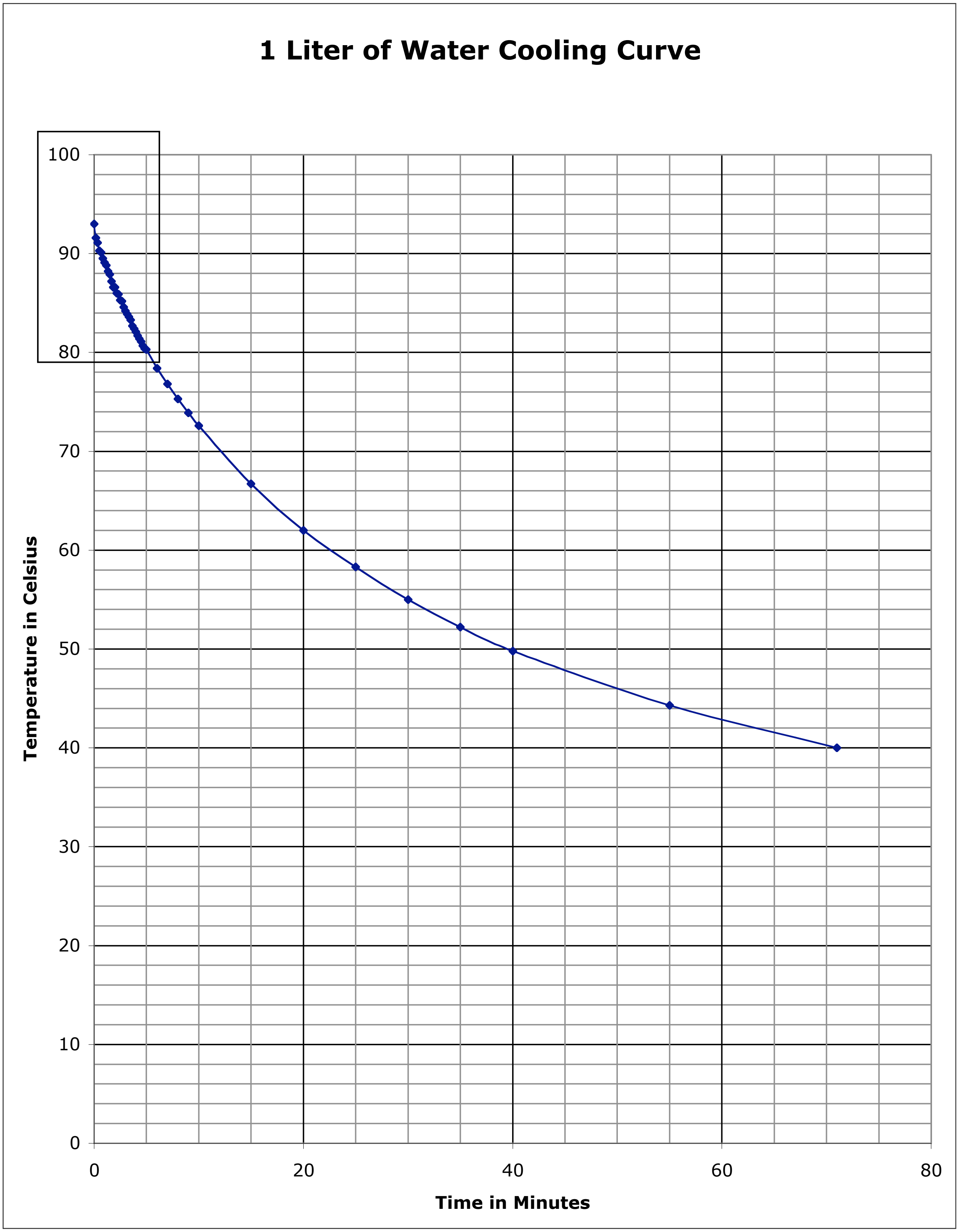
Final Curve: 5 minutes of cooling



Initial Curve: 5 minutes of cooling



This is the final cooling curve. The boxed region represents the first five minutes of cooling.



Temperature Scales

Kelvin, Fahrenheit, and Celsius

Kelvin	Celsius	Fahrenheit
K = C + 273 K = 5/9 (F - 32) + 273	C = K - 273 C = 5/9 (F – 32)	F = 9/5 K – 459.4 F = 9/5 C + 32

	Kelvin	Celsius	Fahrenheit
Water boils	**373**	**100**	**212**
Cup of hot cocoa	333	60	140
Human body temperature	310	37	98.6
Room temperature	294	21	70
Water freezes	**273**	**0**	**32**
Dry Ice (frozen CO_2)	194.5	-78.5	-109.3
Liquid Nitrogen boils	77	-196	-320
Absolute Zero	**0**	**-273**	**-416**

Calculating the Age of the Galaxy

Source: Dr. Harry Shipman's "gut feeling" calculation

Age of the Galactic Disk

Population III stars	**0.01 billion years**

Population III stars are the initial generation of stars that formed in our Galaxy. Theoretically, these stars contained only hydrogen and helium, with a little lithium. No other atomic elements had yet formed. Population III stars theoretically produced atomic elements with atomic numbers greater than 3. Astronomers refer to these elements (lithium to uranium) as *metals*. Computer models of stars that form without metals show that this initial population of stars were massive (many times greater than the Sun) and lived very short lives (a few million years).

Population II stars	**2 billion years**

These stars formed from the remains of the Population III stars. They contained some metals, which changed the range of lifetimes for these stars.

Population I stars

Our Sun is a Population I star. The present generation of stars that formed in our galaxy contains some of the metals produced by the previous generations of stars (Population I and II stars).

White dwarf cooling time:	9 billion (10^9) years
Time to make these white dwarfs from main sequence stars	2 billion years
Main sequence to cool white dwarf	**11 billion years**
Age of our Galaxy	**13 +/- 1 billion years**
Age of the Universe	**14 +/- 1 billion years**

The Next Big Questions Driving New Research

1. How do we know the mass of stars that produce the cool white dwarfs we now observe?

2. How is the mass and luminosity of white dwarfs distributed?

Astronomers call these the *mass function* and *luminosity function.* It's really a histogram that tells you how many white dwarfs have a particular mass or particular luminosity.