Name: Date:

Lab # 4

An Investigation of Meteorites

Instructions: *Numerical answers require units and appropriate numbers of significant digits.* ***Remember to show your work!***

PRELAB

1 Introduction

Meteorites are important because they are samples of the early solar system that have avoided most (or all) of the planetary accretion process and are thus unmodified. They are, by definition, chunks of extraterrestrial material which impact on Earth.

2 Meteorites

Studying meteorites is significant since other than rock samples collected from the Moon, they are the only other direct samples of material from the solar system. Most have been unaltered since the early history of the solar system and using radiometric dating can provide constraints to its age. They provide information on the conditions and composition of the solar nebula, particularly for the inner planets (Mercury, Venus, Earth and Mars). They also help us to understand better the processes involved during planetary differentiation.

Most meteorites are the same age as the solar system, 4.6 billion years ago, but there is a special group (called SNC) which are 1.3 billion years old. There are three main categories of meteorites: Iron, Stony-Iron, and Stony. The stony meteorites are further divided into those which contain chondrules, *Chondrites*, and those which do not, *Achondrites*. Of the Chondrites, there are two main varieties: "ordinary" and "carbonaceous". Now is a good time for you to examine some of the wonderful samples of meteorites held in Northwestern's collection.

2.1 Composition of Meteorites

Iron meteorites are mostly made of iron (*Fe*) and nickel (*Ni*) and they are thought to form at the center of large differentiated planetoids. *Stony-Iron* meteorites, however, are made up of about half metal (*Fe*, *Ni*) and half silicates (like terrestrial rocks). Their composition suggests that they come from intermediate depths in differentiated planetoids.

Stony meteorites have a similar composition to terrestrial ferromagnesian (Fe and Mg rich) sillicates. *Chondrites* are composed of olivine and pyroxene rich *chondrules*, material that is believed to form at high temperature, sorrounded by a low temperature, fine grained matrix (just like chocolate chips cookies). *Carbonaceous Chondrites* are rich in volatile material (carbon) and they are undifferentiated (meaning that they underwent no severe melting to segregate elements within them). As shown in Fig. 1, they are similar in composition to our Sun[1], hence thought to be of similar material which the solar nebula was originally composed.[2] *Ordinary Chondrites* seem to show evidence that they formed in warmer parts of the solar nebula. They have undergone metamorphism, but they are undifferentiated, since this process would have destroyed the structure of the distinct chondrules in their matrices. *Achondrites* have a composition similar to lunar basalts, suggesting they formed as igneous magmas or impacts melts. An abscence of Fe in their composition suggests that they come from differentiated planetoids.

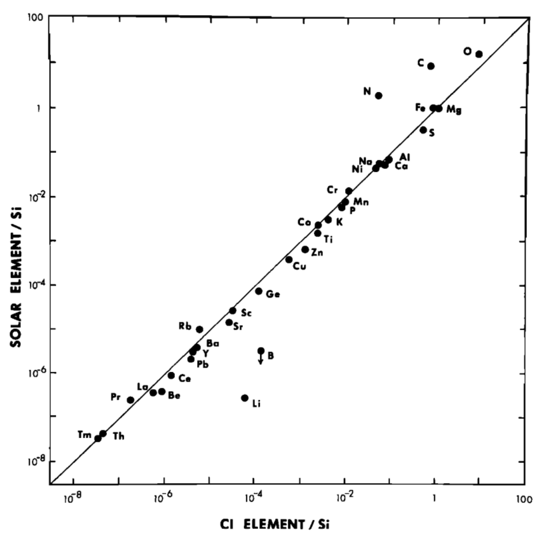

Figure 1: Comparison between Si-normalized elemental abundance for a class of carbonaceous chondrites and the solar atmosphere (after Holweger, 1977).

[1] The terms “chondritic abundance” and “abundance in the Sun” are sometimes used interchangeably.
[2] This is called the chondritic solar system model: same compostion as carbonaceous chondrites.

The different types of meteorited tell us much about geologic processes on and in planetary bodies. Most importantly, they give us information of whether or not they come from differentiated or undifferentiated bodies. The following table summerizes the discussion presented above:

Table 1: Types of Meteorites

Type	**Description**			**Abundance***
Iron	primarily iron and nickel structures within indicate very slow cooling regime, suggests they formed within a relatively large (300–1000km) sized planetoid similar to type M asteroids			5%
Stony Iron	mixtures of iron and stony material indicate that these come from intermediate depths different planetoids like type S asteroids			1%
Stony				94%
	Achondrite	Similar to terrestrial and lunar basalts, absence of Fe, suggesting that these come from differentiated planetoids a few are identical to moon rocks and SNC meteorites		8%
	Chondrite			86%
		Ordinary	have lost their light elements through high temperature metamorphism	82%
		Carbonaceous	very similar in composition to the Sun; less volatiles similar to type C asteroids	4%

* **Abundance:** percentages of each type of meteorite among all meteorites fallen on Earth.

2.2 Meteorites vs. Asteroids

What is the difference between asteroids and meteorites? Asteroids are rocky and metallic objects that orbit the Sun but are too small to be considered planets. They are known as "minor planets". Asteroids range in size from Ceres, which has a diameter of about 1000 km, down to the size of pebbles. The term meteorite comes from the Greek *meteoron*, meaning "phenomenon in the sky", and it refers to any particle of solid matter that has fallen to Earth, the Moon, or another planet, from space. Many meteorites originate as asteroids, others have origins from comets, and pieces of other planets in the solar system.

By the late 18th century it was recognized that the planets orbit at predictable distances from the Sun, but no planet was found between Mars and Jupiter. The asteroid belt was later discovered orbiting in this region, and its locality leads to various for its formation. One theory suggests that it is the remains of a planet which was destroyed in a massive collision long ago. More likely, the asteroids represent material that never coalesed into a planet, possibly perturbed by Jupiter. If the estimated total mass from all asteroids were gathered together, it would form a body less than 1,500 kilometers (932 miles) across, which is less than half the diameter of our Moon.

Sizes, colors, and shapes of asteroids vary. The first asteroid discovered was *Ceres* and it is also the largest. It is classified as C-type, which is the carbon-rich variety. *Gaspra*, *Ida* (both visited by Galileo space craft in 1991 and 1993, respectively), and *Eros* are classified as S-type, composed of metal rich silicates. Other asteroids are classified as M-type, composed mostly of Fe and Ni.

Asteroids have been found inside Earth's orbit to beyond Saturn's orbit. Most are contained within a zone between Mars and Jupiter, called *Main Belt Asteroids*. Others, called *Apollo Asteroids* and *Near Earth Asteroids*, have highly elliptical orbits. These have a higher potential for collision with Earth and may be the source of much meteorite material.

Fig. 2 shows a possible theory for the origin of asteroids, as the source of the various types of meteorites. Here are some possible formation schemes:

A. An undifferentiated body of solar composition forms by accretion;

B. A similar undifferentiated body of solar composition is heated (by radioactive decay) to the point of mild metamorphism, so that it loses some of its volatiles.

C-D. A planetary body is heated to the melting point of metallic iron, initiating differentiation. At this point, dense material would sink to the core, and lighter silicates rise to the crust and mantle.

At any point in these formation sequences, the planetary body could be broken apart (such as Fig. 2.e) forming asteroid material which could later fall to earth as the various meteorites we observe.

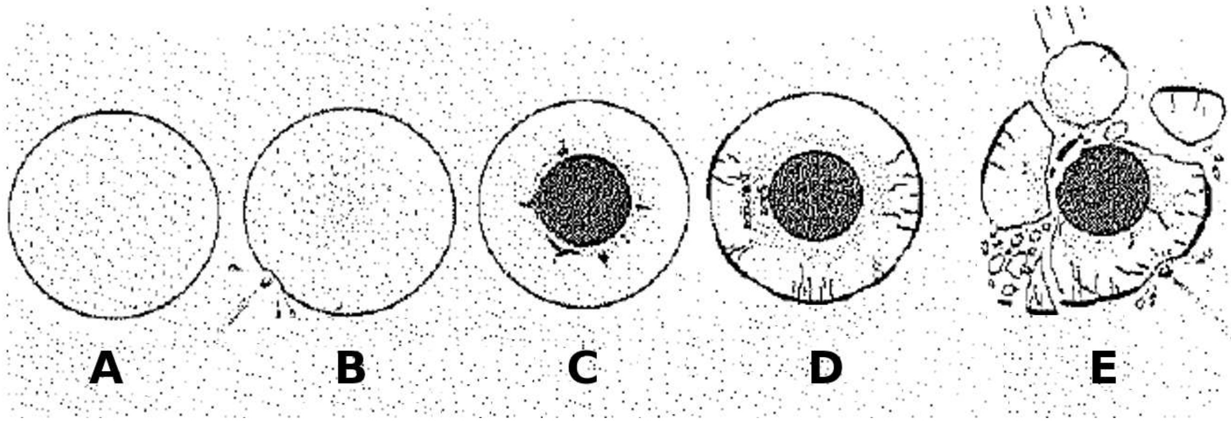

Figure 2: A possible theory for the origin of asteroids. Blue is mantle rock and red is core iron (Asphaug, et al, 2006).

Questions

1. What is the main difference between the two types of stony meteorites, chondrites and achondrites?

2. Fill in the blanks in the following summary using the names of different meteorites. (*Hint: all of the names are in Table 1*)

   An original planetary body of solar nebula composition forms by accretion. If this is frozen in time and not differentiated, it could form ____________ meteorites.

   If heating of a similar planetoid, causes mild metamorphism which drives off some volatiles but does not cause differentiation, ____________ meteorites could form.

   If more intense heating of large sized planetoid occurs, this could cause differentiation. Iron (and heavy elements) would sink to form core where the lighter silicates form the mantles in the planetoids. A thin veneer of lava composed of the lightest silicates could erupt on the surface. If this planetoid is subjected to fragmentation (possibly resulting from impaction), the core components could form ______________ meteorites, core-mantle boundary sections, in addition to the mantle sections could form ______________ meteorites, and the extrusive igneous crustal sections (from the upper 10 km) could form ______________ meteorites. Thus fragmentation of differentiated or undifferentiated bodies could produce the spectrum of observed asteroid and meteorite types.

3. Could a single planetoid give rise to all the various types of meteorites? Explain your answer.

4. What sources of heat may have been important in the thermal evolution of planetoids?

5. Referring to Table 1, what is the most abundant type of meteorite found on Earth? Using your knowledge of the conditions necessary to initiate planetary differentiation, speculate why these meteorites would be most abundant.

6. What class of meteorites is most likely the core of Earth?

3 Impact Craters

When the projectile strikes the surface, it ejects rock from the surface, resulting in a crater. Shortly after the impact, the ground around the initially formed crater begins to collapse inward. The transient crater diameter is the distance from rim to rim of the crater that forms immediately after the impact, before the collapse begins. The final crater diameter, on the other hand, is the distance from rim to rim of the crater once collapse has completed.

We normally collect bits and pieces of meteorites from meteorite impact craters. These craters vary in diameter from a few meters to several kilometers depending on the impactor/target conditions.

The initial diameter and depth of the crater (right after the impact) are called the **"transient diameter"** and **"transient depth"**, but as time goes on, the crater will undergo various changs due to collapses and cooling and as a result the crater diameter will change (normally shrink). The new dimension of the crater, or the so-called **"final diameter"** and **"final depth"** are what we can observe & measure on Earth or terrestrial bodies.

An important factor in describing the meteorites and the resulting impacts is the so-called "depth-to-diameter ratio" as it provides us with a good insight about the impact and the meteorite itself. Let's do this activity to get an idea of how this works.

3.1 Impact: Earth!

A good example of online resources to take a look at general meteorite impact characteristics the Impact: Earth! program.[3] To access the program, use your favorite internet browser to view the following link from the Purdue University[4]:

`http://www.purdue.edu/impactearth/`

[3]You can find a copy of the corresponding scientific paper by Collins *et al.* (2005) in *Meteoritics & Planetary Science* journal at `http://impact.ese.ic.ac.uk/ImpactEffects/effects.pdf`.

[4]An older version of the same program is available at `http://impact.ese.ic.ac.uk/`

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As you can see on this page, you can compute many of the characteristics of the resulting crater, simply by determining a few basic characteristics of the meteorite and the impact target. Try to fill in the following tables by setting some of the fields to the required values.

Question

List 5 of the most important factors affecting the crater size.

A. On the "projectile parameters" column, set the meteorite density to 5500 kg/m^3 (why?). On the "impact parameters" column, leave the "impact angle" at 45° and set the impact velocity to 40 km/s (what is the equivalent in mi/h?). Then, on the "target parameters" column, set the target type to "Sedimentary Rock" and finally, on the bottom row, set the "distance from impact" to 1 km. Now, using different values for the **meteorite diameter** (as listed) fill out the table below.

Meteor. Dia.	T. Dia. (km)	F. Dia. (km)	T. Dep. (km)	F. Dep. (km)	F. Dep / F. Dia	Recurrence Time
30 m						
60 m						
120 m						
250 m						
500 m						
1 km						
2 km						
4 km						
8 km						
16 km						
32 km						
64 km						
128 km						

Questions

1. Using your favorite plotting software, plot the depth-to-diameter ratios for both transient and final dimensions on the same graph and attach the plot to the report you turn in.

2. Do you observe a trend in 1? Explain.

3. Using trial and error, try to figure out the critical impator size at which the impactor does not make it to the ground. Explain.

4. The atomic bomb dropped on Hiroshima released the energy equivalent of $\sim 15,000$ tons of TNT. By keeping the impact velocity and density of the impactor the same as above and setting the angle into vertical, find out how many times of the energy of that bomb would be released from an impactor with a ridius of 50 m.

5. What size is the most probable impactor from the tabel above? Explain.

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B. Now, set the meteorite diameter to 500 m and again on the “impact parameters” column, leave the “impact angle” at 45° and set the impact velocity to 50 m/s. Also, agian, set the target type to “Sedimentary Rock” and the “distance from impact” to 1 km. This time, using the information from

`http://petrowiki.org/File%3AVol1_Page_583_Image_0001.png`

for the **meteorite density** (as listed) fill out the table below.

Meteorite rock	F. Dia. (km)	F. Dep. (km)	F. Dep / F. Dia
ice (=930)			
anorthite			
augite			
iron (=8000)			
hematite			
galena			
garnet			
olivine			
plagioclase			
magnetite			

Questions

1. Using your favorite plotting software, plot the depth-to-diameter ratios for both transient and final dimensions against the meteorite density on the same graph and attach the plot to the report you turn in.

2. Is there a trend in 1? Explain.

3. What happens if you set the “Target Type” to *water*? For the case of an olivine meteorite, set the depth of water to 1000 m and change the “distance from impact” from 1 to 3000 km. Explain your observations.

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3.2 Elevation Profile

In this activity, we are going to use Google Earth to take a look at some “real” meteorite craters. You can download and install the Google Earth software on your computer from `https://www.google.com/earth/`

Setup:

Before you start, change the following settings in your Google Earth program:

- Under “Tools” from the menu bar, click on “Options...” (or “Preferences” under the “Google Earth” botton in Macs”).
- On the “3D View” tab and under “Show Lat/Lon” choose “Decimal Degrees”.
- On the same tab and under “Units of Measurement” check “Meters, Kilometers”.
- On the same tab and under “Terrain”, set the Elevation Exaggerataion to 1.
- At the same place, make sure the “Use 3D Imagery” is checked. Close the dialog box.
- Close the dialog box by hitting OK.
- Under “Layers” at the bottom-left of the screen, uncheck “Photos”.

Cross-Section Tool:

By using the cross-section tool in Google Earth, you can make elevation profiles for any given region on the planet. To do so, you can follow through these steps:

- From the toolbar on the top, choose “Add Path”.
- A dialog box will open on which you can change the attributes of the path you want to make.
- Without closing the dialog box, left-click on a point on the map and without releasing it draw a path (does not have to be straight line).
- When finished, hit “OK” to close the dialog box.
- Now, under “Edit” from the menu bar click on “Show Elevation Profile”.
- The elevation profile for your path will show up on the screen.

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IN LAB

4 Meteorite Samples

Examine the *five* meteorite samples in the lab and answer the following questions.

NOTE: PLEASE DO NOT REMOVE SPECIMEN 25L FROM ITS CONTAINER BOX.

1. List the dominant characterstics of each specimen (at least 4 for each).

2. Use the provided colored pencils to draw simple sketches illustrating some of the major characteristics you have listed above (20 points).

   Important: Please make your sketches as clear as possible. You can use the following or an extra pieces of paper if you need more room. Take your time and avoid drawing small and quick & dirty sketches.

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5 Classes of Meteorites: Specific Gravity

1. Measure the density of specimen 25M, a piece of basalt rock, and an iron nail, using the same methods you used in lab 3 (minerals lab). Use Table

Table 2: Volume and mass values for the aerolite meteorite.

	Mass (g)	V_a (mL)	V_b (mL)	V (mL)	density (g/cm^3)
Aerolite Meteorite (25M)					
Basalt					
Iron Nail					

2. Considering the periodic table of elements (attached to the lab report), which class of meteorites does 25M belong to? Why?

3. Now considering the discussion in the prelab and what we have learned in class, decide about the type of the 25M meteorite.

5.1 The Big Meteorite:

Question

Through examining the big meteorite, and by assuming that it has come from an asteroid formed through the process suggested in Fig. 2, which part of the hypothetical planetoid has this specimen come from? Choose from the list below. Explain your answer.

a. crust

b. crust-mantle boundary

c. mantle transition zones

d. core-mantle boundary

e. core

Which class of meteorites does the big meteorite belong to? Why?

6 Elevation Profiles

The Meteor Crater in Arizona

1. On the "Search" bar at the top left of your screen, type in "35.027 -111.023" and click on "Search".
2. Using different combinations of keyboard & mouse keys, you can rotate the view and observe the crater to get a feeling about its particular shape?
3. Use the cross-section tool to make an elevation profile along the crater's diameter.
4. What are the diameter and depth of the crater? Calculate the depth-to-diamater ratio for the crater.

5. Save the 3D view along with your cross-section by choosing “File > Save > Save Image”. Include the figure in the report you turn in (you do not need to turn in a digital copy for this one).
6. Why is the crater preseved until today?

Question

Using the dimensions of the crater – you can use the “ruler” tool – and assuming that the *iron* impactor was moving at $\sim$ 13 km/s, use the Impact: Earth! online tool to find an estimate on the impactor’s size.

The Lonar Lake in India

1. On the “Search” bar at the top left of your screen, type in “19.976   76.508” and click on “Search”.
2. Using different combinations of keyboard & mouse keys, you can rotate the view and observe the crater to get a feeling about its particular shape?
3. Use the cross-section tool to make an elevation profile along the crater’s diameter.
4. What are the diameter and depth of the crater? Calculate the depth-to-diamater ratio for the crater.

5. Save the 3D view along with your cross-section by choosing “File ¿ Save ¿ Save Image”. Include the figure in the report you turn in (you do not need to turn in a digital copy for this one).

Questions

1. Using the dimensions of the crater – you can use the “ruler” tool – and assuming that the *iron* impactor was moving at ~ 13 km/s, use the Impact: Earth! online tool to find an estimate on the impactor’s size.

2. How do the two ratios for the Meteor Crater and the Lonar Lake compare?

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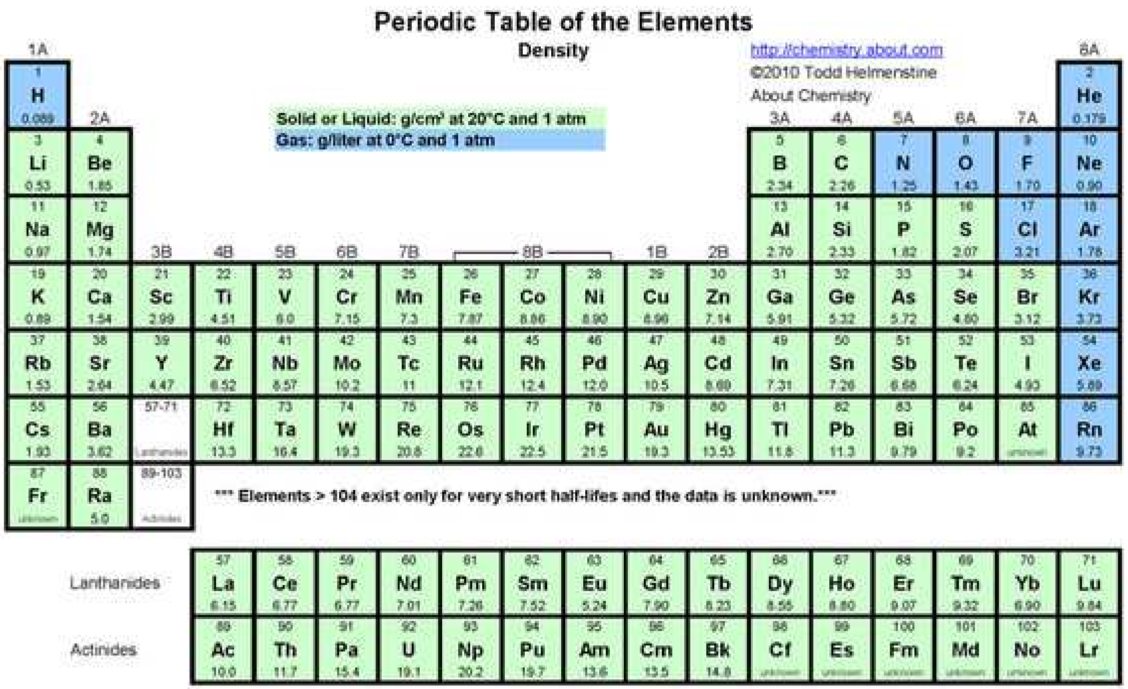

Periodic Table of the Elements

Density

http://chemistry.about.com
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About Chemistry

Solid or Liquid: g/cm³ at 20°C and 1 atm
Gas: g/liter at 0°C and 1 atm

1A	2A	3B	4B	5B	6B	7B	8B	8B	8B	1B	2B	3A	4A	5A	6A	7A	8A
1 H 0.089																	2 He 0.179
3 Li 0.53	4 Be 1.85											5 B 2.34	6 C 2.26	7 N 1.25	8 O 1.43	9 F 1.70	10 Ne 0.90
11 Na 0.97	12 Mg 1.74											13 Al 2.70	14 Si 2.33	15 P 1.82	16 S 2.07	17 Cl 3.21	18 Ar 1.78
19 K 0.89	20 Ca 1.54	21 Sc 2.99	22 Ti 4.51	23 V 6.0	24 Cr 7.15	25 Mn 7.3	26 Fe 7.87	27 Co 8.86	28 Ni 8.90	29 Cu 8.96	30 Zn 7.14	31 Ga 5.91	32 Ge 5.32	33 As 5.72	34 Se 4.80	35 Br 3.12	36 Kr 3.73
37 Rb 1.53	38 Sr 2.64	39 Y 4.47	40 Zr 6.52	41 Nb 8.57	42 Mo 10.2	43 Tc 11	44 Ru 12.1	45 Rh 12.4	46 Pd 12.0	47 Ag 10.5	48 Cd 8.69	49 In 7.31	50 Sn 7.26	51 Sb 6.68	52 Te 6.24	53 I 4.93	54 Xe 5.89
55 Cs 1.93	56 Ba 3.62	57-71 Lanthanides	72 Hf 13.3	73 Ta 16.4	74 W 19.3	75 Re 20.8	76 Os 22.6	77 Ir 22.5	78 Pt 21.5	79 Au 19.3	80 Hg 13.53	81 Tl 11.8	82 Pb 11.3	83 Bi 9.79	84 Po 9.2	85 At unknown	86 Rn 9.73
87 Fr unknown	88 Ra 5.0	89-103 Actinides															

*** Elements > 104 exist only for very short half-lifes and the data is unknown.***

Lanthanides	57 La 6.15	58 Ce 6.77	59 Pr 6.77	60 Nd 7.01	61 Pm 7.26	62 Sm 7.52	63 Eu 5.24	64 Gd 7.90	65 Tb 8.23	66 Dy 8.55	67 Ho 8.80	68 Er 9.07	69 Tm 9.32	70 Yb 6.90	71 Lu 9.84
Actinides	89 Ac 10.0	90 Th 11.7	91 Pa 15.4	92 U 19.1	93 Np 20.2	94 Pu 19.7	95 Am 13.6	96 Cm 13.5	97 Bk 14.8	98 Cf unknown	99 Es unknown	100 Fm unknown	101 Md unknown	102 No unknown	103 Lr unknown

Figure 3: The periodic table of elements.