Imagine the effects of a large asteroid slamming into the Earth at high velocity.
Earth’s Place in Space: The Scientific Belief

- The origins of the universe began with the “Big Bang”: ~ 14 billion years ago.
  - This explosion produced atomic particles that make up all matter.

- The first stars probably formed ~ 13 billion years ago.
  - The lifetime of stars depends on the mass that created them.
    - Surprisingly (?), large stars burn up more quickly, and last ~100,000 years.
    - Smaller stars, like our sun live ~10 billion years.
  - **Supernovas** signal the death of a star.
    - This releases massive amounts of energy and shock waves.

Keller and Blodgett PowerPoint, 2007
Earth’s Place in Space, cont.

• ~4.6 billion years ago, a supernova explosion triggered the formation of our sun.
  – The Sun grew by the buildup of matter from a solar nebula.
    • With time, this became a pancake of rotating hydrogen and helium dust.
• After the formation of the Sun, other particles were trapped in the rings.
  – Particles in the rings attracted other particles and collapsed into planets.
  – Pre-Earth (a molten magma ball) was hit by objects, adding to its formation; Like a large water drop colliding and combing with smaller water droplets.
    • Although thankfully by not as much, bombardment of this material continues today.
### Sources of Extraterrestrial Debris

#### Major Components of the Solar System

<table>
<thead>
<tr>
<th></th>
<th>Diameter $(10^3 \text{ km})$</th>
<th>Diameter (Miles)</th>
<th>Specific Gravity $(\text{Water} = 1)$</th>
<th>Gravity $(\text{Earth} = 1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sun</strong></td>
<td>1,395</td>
<td>864,886</td>
<td>1.4</td>
<td>27.9</td>
</tr>
<tr>
<td><strong>Inner rocky planets</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mercury</td>
<td>4.88</td>
<td>3,024</td>
<td>5.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Venus</td>
<td>12.13</td>
<td>7,522</td>
<td>5.3</td>
<td>0.9</td>
</tr>
<tr>
<td>Earth</td>
<td>12.77</td>
<td>7,918</td>
<td>5.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Moon</td>
<td>3.48</td>
<td>2,160</td>
<td>3.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Mars</td>
<td>6.77</td>
<td>4,200</td>
<td>3.9</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Asteroid belt</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Outer ice and gas planets</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jupiter</td>
<td>139.8</td>
<td>86,692</td>
<td>1.3</td>
<td>2.7</td>
</tr>
<tr>
<td>Saturn</td>
<td>116.7</td>
<td>72,352</td>
<td>0.7</td>
<td>1.1</td>
</tr>
<tr>
<td>Uranus</td>
<td>47.0</td>
<td>29,168</td>
<td>1.6</td>
<td>1.1</td>
</tr>
<tr>
<td>Neptune</td>
<td>45.5</td>
<td>28,230</td>
<td>2.3</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Dwarf planet</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pluto</td>
<td>11.4</td>
<td>7,084</td>
<td>1.7</td>
<td>0.2</td>
</tr>
</tbody>
</table>

*Source: R. T. Dodd (1986)*
Sources of Extraterrestrial Debris Are:

- Primarily from fragmented asteroids.
- & secondarily from comets.

Pieces of asteroids and comets orbiting the Sun = meteoroids

Meteoroids blazing through Earth’s atmosphere = shooting stars or meteors

Meteors that hit the Earth’s surface = meteorites

- Irons: metallic meteorites (most of collected meteorites)
- Stones: rocky meteorites (most of meteorites)
- Stony Irons: A rare mixture of the two.

Abbott PowerPoint, 2009
Sources of Extraterrestrial Debris

Asteroids

- The Solar System consists of: 4 small, rocky inner planets + 4 large, gaseous outer planets (+ sub planetoids Pluto, Sedna, Eris, and 1000’s of others)
- Between Mars and Jupiter lies the asteroid belt. It contains many small (under 1,000 km diameter) rocky, metallic and icy masses.
- Most meteorites, it’s presumed, come from the inner Solar System. Specifically, from the asteroid belt.
Sources of Extraterrestrial Debris

Minor Components of the Solar System

Asteroids

- It is estimated that, together, all the asteroids in the solar system would have formed a planet less than half the Earth’s Moon’s diameter. A majority of those in the asteroid belt were not able to form together because Jupiter’s gravitational pull continues to pull them apart from one another.

- Many asteroids, like Ida and Dactyl, are held together with other asteroids by gravity.

Abbott PowerPoint, 2009

The asteroid *Ida* is 56 km (35 mi) long and pockmarked with impact craters. Traveling with *Ida* is its near-spherical moon *Dactyl* with dimensions of 1.2 x 1.4 x 1.6 km.
Asteroids

- Asteroids are often referred to as “minor planets”, and are usually less than 1 km long.
- Calculations imply that most Earth-crossing asteroids (an asteroid whose orbit crosses that of the Earth) will eventually collide with Earth, and that during any given million-year period, our planet is struck by at least one. Several dozen large basins and eroded craters on Earth are suspected to be sites of ancient asteroid collisions. The many large impact craters on the Moon, Venus, and Mars are direct evidence of similar events on those worlds.

Nelson, 2004
Comets

• Are described by astronomers as “dirty snowballs”. They are composed of ice and rocky debris.
• When they pass Saturn (heading toward the Sun), comets are affected by sunlight and solar wind. Sublimation (conversion of a solid (ice) directly to a gas) releases gas and dust to form a tail. (See 2 slides past for further detail.)
• Nearer to the Sun, its tail becomes larger; Always pointing away from Sun! (The tail does not necessarily show the direction of travel of the comet.)
• Comets contain carbon compounds (CHON – carbon, hydrogen, oxygen, nitrogen), which are the building blocks of life. It is has been theorized that these chemicals were first brought to Earth by comets.
Comets

- Are classified as having a **short-period** (< 200 years) of revolution (around the sun) or a **long-period** (> 200 years).

- The Solar System is surrounded by:
  - About one billion comets that are estimated to be in the **Kuiper belt** — a flattened disk (in the plane of the Solar System) from near Neptune to about 50 astronomical units. (See next slide for a diagram.)
  - About one trillion comets are in the **Oort cloud** — spherical orbits far beyond the planets. (See next slide for a diagram.)
Comets

- Few comets from the Kuiper belt or Oort cloud with very elliptical orbits actually enter the Solar System, but still may impact planets.

Sources of Extraterrestrial Debris

Chaisson, et al. 2008

Abbott PowerPoint, 2009
(a) This is a diagram of a typical comet, showing the nucleus, coma, hydrogen envelope, and tail. The tail is not a sudden streak in time across the sky, as in the case of meteors or fireworks. Instead, it travels along with the rest of the comet as long as the comet is close enough to the Sun.

(b) A photograph of Halley's Comet (from a telescope on Earth) in 1986, about one month before it rounded the Sun.
As it approaches the Sun, a comet develops an ion tail, which is always directed away from the Sun. Closer in, a curved dust tail, also directed generally away from the Sun, may appear. Notice that the ion tail always points directly away from the Sun on both the inbound and the outgoing portion of the orbit. The dust tail has a marked curvature and tends to lag behind the ion tail.

Comets slowly break up when near the Sun, due to Solar radiation, wind and tidal force. e.g. Halley loses ~10 tons/sec when near Sun. At that pace, it should be “eroded away” in 40,000 years.
Visiting Halley’s Comet

(a) The Giotto spacecraft was sent by the European Space Agency to Halley’s Comet on July 2, 1985 to study and photograph it. Giotto caught up with it on March 14, 1986 (at a distance of 529 km between the two). It resolved the nucleus of it in this photograph, showing it to be very dark. Although, heavy dust in the area obscured any surface features. The Sun is toward the right in this image. The brightest areas are jets of evaporated gas and dust spewing from the comet's nucleus.

(b) A diagram of the nucleus of Halley's Comet.

Williams, 2005
Chaisson, et. al. 2008
Bell., 2009
(a) A **stony meteorite** often has a dark crust, created when its surface is melted by the tremendous heat generated during passage through the atmosphere.

(b) **Iron meteorites** are rarer than stony ones, and usually contain some nickel as well. Most iron meteorites show characteristic crystalline patterns when their surfaces are cut, polished, and etched with acid.

- **Stones** which are the most abundant type.
- **Irons** which are composed mostly of iron.
- **Stony-irons** are extremely rare and are a mixture of both.

Chaisson, et. al. 2000
What Can We Learn from Meteorites?

• They provide clues about the formation of the Solar System.
  – It is believed that material from the origin of the Solar System melted to form planets, and some of these pieces were knocked off of these planets or moons and still contain the original material.
  – Some probably still have original material of the solar nebula and have not been melted together.
  – Using thermoluminescence dating of confirmed meteorite material, the age of the Solar System was calculated to be about 4.6 billion years old. Thus, this material has allowed for study of the universe’s age, as well.

Burns, et. al. 2005

How the Earth Was Made (Season 1): Asteroids, 2009
Meteors and Meteoroids

• Recall:
  – that a **meteoroid** is a rock or an icy fragment traveling in space. They can range in size from sand grains to large boulders.
  – A **meteor** is the light made by a meteoroid as it passes through Earth’s atmosphere. The light is caused by friction between air molecules in Earth's atmosphere and meteoroid.

*The Northern Lights provide the background for a brighter meteor trail.*

Chaisson, et. al. 2000
A meteoroid swarm associated with a given comet or asteroid intersects Earth's orbit at specific locations, giving rise to meteor showers at specific times of the year.

Chaisson, et. al. 2008
## Some Prominent Meteor Showers Throughout the Year

<table>
<thead>
<tr>
<th>MORNING OF MAXIMUM ACTIVITY</th>
<th>SHOWER NAME/RADIANT</th>
<th>ROUGH HOURLY COUNT</th>
<th>PARENT COMET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan. 3</td>
<td>Quadrantid/Bootes</td>
<td>40</td>
<td>—</td>
</tr>
<tr>
<td>Apr. 21</td>
<td>Lyrid/Lyra</td>
<td>10</td>
<td>18611 (Thatcher)</td>
</tr>
<tr>
<td>May 4</td>
<td>Eta Aquarid/Aquarius</td>
<td>20</td>
<td>Halley</td>
</tr>
<tr>
<td>June 30</td>
<td>Beta Taurid/Taurus</td>
<td>25</td>
<td>Encke</td>
</tr>
<tr>
<td>July 30</td>
<td>Delta Aquarid/Aquarius/Capricorn</td>
<td>20</td>
<td>—</td>
</tr>
<tr>
<td>Aug. 12</td>
<td>Perseid/Perseus</td>
<td>50</td>
<td>1862III (Swift–Tuttle)</td>
</tr>
<tr>
<td>Oct. 9</td>
<td>Draconid/Draco</td>
<td>up to 500</td>
<td>Giacobini–Zimmer</td>
</tr>
<tr>
<td>Oct. 20</td>
<td>Orionid/Orion</td>
<td>30</td>
<td>Halley</td>
</tr>
<tr>
<td>Nov. 7</td>
<td>Taurid/Taurus</td>
<td>10</td>
<td>Encke</td>
</tr>
<tr>
<td>Nov. 16</td>
<td>Leonid/Leo</td>
<td>12(^1)</td>
<td>1866I (Tuttle)</td>
</tr>
<tr>
<td>Dec. 13</td>
<td>Geminid/Gemini</td>
<td>50</td>
<td>3200 Phaeton(^2)</td>
</tr>
</tbody>
</table>

\(^1\)Every 33 years, as Earth passes through the densest region of this meteoroid swarm, we see intense showers that can reach 1000 meteors per minute for brief periods of time. This occurred most recently in 1999 and 2000.

\(^2\)Phaeton is actually an asteroid and shows no signs of cometary activity, but its orbit matches the meteoroid paths very well.

Chaisson, et. al. 2008
### Natural Space Debris Reference Table

<table>
<thead>
<tr>
<th>Type</th>
<th>Diameter</th>
<th>Composition</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asteroid</td>
<td>10 m to 1000 km</td>
<td>Stony or metallic</td>
<td>Strong and hard if made of metal or some rock types; hard types may hit Earth, and weak types will explode in Earth’s atmosphere at heights of several to hundreds of kilometers. Most originate in asteroid belt between Mars and Jupiter.</td>
</tr>
<tr>
<td>Comet</td>
<td>A few meters to a few hundred kilometers</td>
<td>Frozen water and/or carbon dioxide form an icy core that is surrounded by rock fragments and dust; like a “dirty snowball”</td>
<td>Weak, porous, will often explode in Earth’s atmosphere at heights of kilometers to hundreds of kilometers; Most originate outside solar system in the Oort Cloud, 50,000 AU(^1) from the Sun, or within the solar system in the Kuiper Belt of comets; A tail, pointed away from the sun, forms as the icy core vaporizes and dust particles are shed from the object.</td>
</tr>
<tr>
<td>Meteoroid</td>
<td>Less than 10 m to larger than dust size</td>
<td>Stony, metallic, or carbonaceous (contains carbon)</td>
<td>Most originate from collisions of asteroids or comets. May be made of strong or very weak rock.</td>
</tr>
<tr>
<td>Meteor</td>
<td>Centimeters to dust size</td>
<td>Stony, metallic, carbonaceous, or icy</td>
<td>Destroyed in Earth’s atmosphere as “shooting stars”; their light is produced by frictional heating in the atmosphere.</td>
</tr>
<tr>
<td>Meteorite</td>
<td>Centimeters to asteroid size</td>
<td>Stony, metallic, or carbonaceous</td>
<td>Object that has actually hit Earth’s surface. Stony variety, called a chondrite, is most abundant.(^2)</td>
</tr>
</tbody>
</table>

\(^1\)AU is the distance from Earth to the Sun, about \(150,000,000\) km (\(93,000,000\) mi.).

\(^2\)There are many types of chondrites. They contain chondrules, which are small (less than 1 mm) spheroidal inclusions that are glassy or crystalline. Planets are constructed from chondrite meteorites (asteroids).

Meteorite/ Asteroid Craters on Earth

This photograph shows the ancient impact basin that forms Quebec's Manicouagan Reservoir. A large meteorite landed there about 200 million years ago. The central floor of the crater rebounded after the impact, forming an elevated central peak. The lake, 70 km in diameter, now fills the resulting ring-shaped depression.

The Barringer Meteor Crater, near Winslow, Arizona, is 1.2 km in diameter and 0.2 km deep, the result of a meteorite impact about 49,000 years ago. The meteoroid was probably about 50 m across and likely weighed around 200,000 tons.

Chaisson, et. al. 2008
• There are 164 known impact craters in the world, including 57 in U.S. and Canada. The closest to Western New York is the Brent Crater in Southern Ontario.
• With the constant processes of plate tectonics and weathering and erosion, many more impact craters may have worn away in the millions of years in Earth’s existence.
The Crater-Forming Process

• The energy release of an impact depends on the object’s speed + mass.
  – Asteroids are estimated to impact at 14 km/sec, while comets could hit at 70 km/sec!
• Impacts of smaller meteorites form simple craters (i.e. Meteor Crater, Arizona)
• Impacts of larger bodies form complex craters.
  - Some examples are: The buried Chicxulub crater on the Yucatan Peninsula, Mexico and the Manicouagan crater in Canada.
Simple Impact Craters

- These are typically; < 6 km (4 mi)
- Ex. Barringer Crater, AZ
Complex Impact Craters

- These are larger in diameter; > 6 km (4 mi)
- Their rims collapse more completely.
- Their centers tend to uplift following impact.
- Ex: Quebec's Manicouagan Reservoir

Crater Profile

Keller and Blodgett, 2007
The Evidence of An Impact Crater

• “Typical” evidence of meteorite/comet/asteroid impacts.
  – Bowl-shaped depressions with an upraised rim.
  – Rim is overlain by an ejecta blanket.
  – Broken rocks (below the crater) are cemented together into breccia.

• Features of impact craters are unique from other natural craters.
  – Impacts involve high velocity, energy, pressure, and temperature.
  – The kinetic energy of an impact produces a shock wave into the earth.
    • This compresses, heats, melts, and excavates materials.
  – Rocks at the impact site become metamorphosed or melt with other materials.
  – Some have raised centers.
    • Just as a drop of water shows:

As a drop of water hits a larger body of water, notice the central rebound.

Keller and Blodgett, 2007

Abbott, 2009
The Mechanics of Impact Cratering

When a large, fast moving object enters the Earth's atmosphere, the initial impact with the atmosphere will compress the atmosphere, sending a shock wave through the air. Frictional heating will cause the object to heat and glow. Melting and even vaporization of the outer parts of the object will begin, but if the object is large enough, solid material will remain when it impacts the surface of the Earth.

Sometimes, the object will explode in the atmosphere before making contact with the ground. This is called an airburst, and could actually be more dangerous than an impacting explosion. Once such event happened in the remote region of the Tunguska region of Siberia in 1908.

-(See the next few slides for further details.)
Impacts of large meteorites (on Earth) have never been observed by humans. Much of our knowledge about what happens next must come from scaled experiments and observations from space (Two separate comets, one in 1994 and the other in July of 2009, were observed to hit Jupiter).

As a large, solid object plows into the Earth, it will compress the rocks to form a depression and cause a jet of fragmented rock and dust to be expelled into the atmosphere. This material is called *ejecta*.

Recall that the impact will send a shock wave into the rocks below, and the rocks will be crushed into small fragments to form a *breccia*. Some of the ejecta will be hot enough to vaporize (turn into a gas), and the heat generated by the impact could be high enough to actually melt the rock at the site of the impact!

The shock wave entering the Earth will first move in as a compressional wave (P-wave), but after passage of the compressional wave an expansion wave (rarefaction wave) will move back toward the surface. This will cause the floor of the crater to be uplifted and may also cause the rock around the rim of the crater to bent upward. Faulting may also occur in the rocks around the crater, causing the crater to become enlarged, and have a concentric set of rings.

The ejecta will eventually settle back to the Earth's surface forming an *ejecta blanket* that is thick near the crater rim and thins outward from the crater. Rocks below the crater that were not melted by the impact will be intensely fractured. All of this would happen in a matter of seconds!

Nelson, 2004

*NASA - Hubble Space Telescope Captures Rare Jupiter Collision, 2009*
Meteorite Flux and Size

- **Meteorite flux** is the total mass of extraterrestrial objects that strike the Earth. This is currently about 100 to 1,000 tons of material to Earth’s surface each day or $10^7$ (1,000,000) to $10^9$ (100,000,000) kg/year!
  - Since more than 2/3’s of Earth’s surface is covered by ocean water, much of it lands here.

- Much of this material is a dust-sized object called a **micrometeorite**. The frequency at which meteorites of different sizes strike the Earth depends on the size of the objects, as shown in the graph on the next slide.
  - Tons of micrometeorites strike the Earth each day. Because of their small size, they do not usually burn up when entering the Earth's atmosphere, but instead settle slowly to the surface. In fact, much of this dust helps create condensation nuclei which allow clouds to form in the atmosphere. Meteorites with diameters of about 1 mm strike the Earth about once every 30 seconds.
  - Meteorites of larger sizes strike the Earth less frequently. If they have a size greater than about 2-3 cm, they only partially melt or vaporize on their passage through the atmosphere, and thus strike the surface of the Earth.
  - Objects with sizes greater than 1 km are considered to produce effects that would be catastrophic, because an impact of such an object would produce global effects. Such meteorites strike the Earth relatively infrequently - a 1 km sized object strikes the Earth about once every million years, and 10 km sized objects about once every 100 million years.

Nelson, 2004
Rates of Meteoroid Influx

• 1 trillion or more micro-meteoroids enter Earth’s atmosphere every day!

• Smaller meteoroids → greater abundance

Keller and Blodgett, 2007
The Journey of Meteorites to the Surface

- Meteoroids of 1 gram or more can pass through the atmosphere to Earth’s surface (if its angle of travel doesn’t deflect it back to outer space).
- Frictional resistance of the atmosphere melts away the meteoroid’s exterior, exposing the protected interior, which in-turn creates a glazed, blackened crust.
- The quick moving meteoroid violently compresses the air, creating a mini-sonic boom.
- The atmospheric frictional heat may raise the surface temperature of a meteoroid to 3,000°C, creating a tail to a fireball!
Rates of Meteoroid Influx – Recent Impacts

Meteorites

• 1938: A small meteorite crashed through the roof of a garage in Illinois.
• 1954: A 5kg stony meteorite crashed through roof of an Alabama home, bounced off the walls then hit a woman in the hip, severely bruising her.

This was the only known person to have survived a direct meteorite hit until June of 2009! Some of the damage to the home can be seen in the picture to the right.

Keller and Blodgett, 2007
Nelson, 2004
Abbott PowerPoint, 2009
Rates of Meteoroid Influx – Recent Impacts (cont.)

Meteorites

• 1992: A small meteorite put a hole in the trunk of a car in Peekskill, New York. (See video.)

• October, 1996: A meteorite streaked over New Mexico and Texas, bounced into space, was pulled back to Earth and fell in California.

• March, 2003: A meteorite flashed over the Midwest of the US as it broke apart. More than 60 pieces were found, hitting homes, cars and a fire department structure.

• September, 2003: A large meteorite broke apart over Orissa, India, raining debris that injured three people and set a house on fire.

• NEA 2008 TC3 is the first meteorite to be discovered before impact (October 7, 2008). The explosion point in northern Sudan was determined with sufficient accuracy to allow later recovery of it.
Rates of Meteoroid Influx – Recent Impacts (cont.)

Meteorites

• November, 2008: A desk-sized meteor flashed across the sky just after sunset, lighting up the sky over south central Canada. Chunks of it landed in Lloydminster, Saskatchewan. In total, more than one thousand meteorite fragments have been collected from the 10-ton fireball, among them are two 13 kg fragments.

• June, 2009, Germany: Gerrit Blank was on his way to high school when he saw a massive fireball heading straight towards him from the sky. The white-hot meteorite skimmed off the 14 year-old’s hand and hit the ground so hard it left a foot-long crater in the street as well as a three-inch scar on his hand.

• Meteorite fragments have been found all over the surface of the Earth, although most have been found in Antarctica. In Antarctica they are easily seen on the snow covered surface or embedded in ice.

"Boy Hit On Arm By White-Hot Meteorite From Outer Space Travelling At 30,000mph", 2009

CTV News | 10,000 meteorites touched down in Sask., 2008

Nemiroff and Bonnell, 2008

Nelson, 2004
A Close Call from an Airburst

The explosion of an asteroid in the atmosphere is thought to have occurred in the Tunguska region of Siberia more than 100 years ago. The blast was about the size of a 15 megaton nuclear bomb. It knocked down trees in an area about 850 square miles, but did not leave a crater.

“A century later, some still debate the cause and come up with different scenarios that could have caused the explosion,” says Don Yeomans, manager of the Near-Earth Object Office at NASA's Jet Propulsion Laboratory. “But the generally agreed upon theory is that on the morning of June 30, 1908, a large space rock, about 120 feet across, entered the atmosphere of Siberia and then detonated in the sky.”

It is estimated the asteroid entered Earth's atmosphere traveling at a speed of about 33,500 miles per hour. During its quick plunge, the 220-million-pound space rock heated the air surrounding it to 44,500 °F. At 7:17 a.m. (local Siberia time), at a height of about 28,000 feet, the combination of pressure and heat caused the asteroid to fragment and annihilate itself, producing a fireball and releasing an energy equivalent to about 185 Hiroshima bombs!

“That is why there is no impact crater,” said Yeomans. “The great majority of the asteroid is consumed in the explosion.” This is now known as an airburst. Only small amounts of material similar to meteorites were found embedded in trees at the site.
A Close Call from an Airbust – cont.

The Tunguska region today

The Tunguska Event--100 Years later, 2008

The Tunguska Event, 2010

The Tunguska Region; 19 years after the event!
Notice the burned, knocked-down trees?

Morrison, 2006
Some asteroids have orbits that bring them close to Earth, but NOT crossing Earth’s orbit. These are called **Amor objects**.

Some have orbital paths that cross the orbital path of the Earth. These are called **Earth-crossing asteroids (ECA’s) or Apollo objects**.

All objects that have a close approach to the Earth are often referred to as **Near Earth Objects or NEO’s**, specifically defined as asteroids or comets whose orbits have come within less than 1.3 AU’s. There is a subset of NEO’s that pose a more immediate threat to Earth, called Potentially Hazardous Objects (PHO’s). PHO’s are defined as asteroids and comets that pass within 0.05 AU of Earth’s orbit and are large enough to cause significant damage should one impact Earth (~50 meters in diameter and larger).
What size NEO’s are dangerous?

The Earth's atmosphere protects us from most NEO’s smaller than a modest office building (~50 m diameter, or impact energy of about 3 megatons). From this size up to about 1 km diameter, an impacting NEO can do tremendous damage on a local scale.

Above an energy of a million megatons (diameter about 2 km), an impact will produce severe environmental damage on a global scale. The probable consequence for survivors would be an "impact winter" with loss of crops worldwide and subsequent starvation and disease.

Still larger impacts can cause mass extinctions, like the one that is believed to have ended the age of the dinosaurs 65 million years ago (15 km diameter and about 100 million megatons).

Morrison; "FAQs About NEO Impacts.", 2004
How Many NEO’s Exist?

There are many more small NEO’s than large ones. Astronomers estimate that there are approximately 1100 Near-Earth Asteroids (NEA’s) larger than 1 km in diameter, and more than a million larger than 50 m in diameter (the approximate threshold for penetration through the Earth's atmosphere). The largest NEA’s are less than 25 km in diameter. There are probably many more comets than NEA’s, but they spend almost all of their lifetimes at great distances from the Sun and Earth, so that they contribute only about 10% to the census of larger objects that strike the Earth, and probably less than 1% of NEO’s less than 1 km in diameter.

Morrison; "FAQs About NEO Impacts.", 2004
Who is Searching for NEO’s?

Several teams of astronomers worldwide are surveying the sky with electronic cameras to find NEO’s, but the total effort involves fewer than 100 people! The most productive NEO survey is the LINEAR search program of the MIT Lincoln Lab, carried out in New Mexico with US Air Force and NASA support. The LINEAR team, which operates two search telescopes, discovers more asteroids than all the other searches combined.

Other active US survey groups include the NEAT search program in Hawaii, carried out jointly by the NASA Jet Propulsion Lab and the US Air Force; the Spacewatch survey at the University of Arizona, funded by NASA and a variety of private grants, the LONEOS survey at Lowell Observatory in Flagstaff Arizona, supported by NASA grants, and the Catalina Sky Survey in Tucson Arizona, also supported by NASA. Other astronomers (many of them amateurs) follow up the discoveries with supporting observations.

Morrison; "FAQs About NEO Impacts.", 2004
What is the U.S. Government Doing to Protect US?

The US Congress held hearings to investigate the impact hazard in 1993, 1998, and 2002, where both NASA and the US Air Force supported surveys to discover NEO’s. In 1998, NASA formally initiated the *Spaceguard Survey* by adopting the objective of finding 90% of the NEA’s larger than 1 km diameter within the next decade (that is, before the end of 2007).

In 1998 NASA also created a NEO Program Office, and today $3-4 million per year is being spent on NASA-supported NEO searches and orbit calculations.

“On December 28, 2005, the United States Congress passed Section 321 of the NASA Authorization Act of 2005 (Public Law No. 109-155), also known as the George E. Brown, Jr. Near-Earth Object Survey Act. The objectives of the George E. Brown, Jr. NEO Survey Program are to detect, track, catalogue, and characterize the physical characteristics of NEO’s equal to or larger than 140m in diameter with a perihelion distance of less than 1.3 AU from the Sun, achieving 90 percent completion of the survey within 15 years after enactment of the NASA Authorization Act of 2005. The Act was signed into law by President Bush on December 30, 2005.” Although law, the continued cost for satellite and telescope creation, along with the cost of researchers, will probably halt the project in the next few years.

NASA’s on-going data collection, as presented on the next slide, shows the need for researching the heavens above for potentially dangerous impacting objects. Thousands for NEO’s have been discovered since they started the Survey in 1998, and many more are likely to be found.

Other governments have thankfully expressed concern about the NEO hazard, and have began funding extensive surveys and related defense research.

Bekey, 2009        Morrison; "FAQs About NEO Impacts.", 2004
What Has Been Found Thus Far by the *Space Guard Survey*?

**Known Near-Earth Asteroids**
1980-Jan through 2009-Sep

- **All NEAs**
- **Large NEAs**

23 October 2009
Alan B. Chamberlin (JPL)
Velocity and Energy Release of Incoming Objects

The velocities at which small meteorites impact the Earth range from 4 to 40 km/sec. Larger objects would not be slowed down much by the friction associated with passage through the atmosphere, and thus would impact the Earth with a high velocity. Calculations show that a meteorite, like the one that created the Barringer Crater in Arizona, would release an energy equivalent to about 20 million (20,000,000) tons of TNT.

The amount of energy released by an impact depends on the size of the impacting body and its velocity. An impact like the one that struck the Yucatan Peninsula, in Mexico about 65 million years ago, thought responsible for the extinction of the dinosaurs and numerous other species, created the Chicxulub Crater, 180 km in diameter and released energy equivalent to about 100 million megatons (100,000,000,000,000 tons) of TNT.

For comparison, the amount of energy needed to create a nuclear winter on the Earth as a result of nuclear war is about 8,000 megatons (8,000,000,000 tons), and the energy equivalent of the world's nuclear arsenal is about 60,000 megatons (60,000,000,000 tons)!

Nelson, 2004
The Approximate Frequency of Impacts with Earth and Their Megatons of TNT Energy Equivalent

- Monthly
- Every year
- Every decade
- Once a century
- Once a millennium
- Every ten thousand yr
- Every 100 thousands yr
- Every million yr
- Every 10 million yr

Megatons TNT equivalent energy

1/100 1 100 10,000 1 100

Million Million

“Annual event” ~20 kilotons
“1000 year event” ~50 megatons
Extinction of the dinosaurs
Global catastrophe threshold

Tunguska

Chaisson, et. al. 2008
Meteorite/ Asteroid/ Comet Impacts and Mass Extinctions

The impact of a space object with a size greater than about 1 km would be expected to be felt over the entire surface of the Earth. Smaller objects would certainly destroy the ecosystem in the vicinity of the impact, similar to the effects of a volcanic eruption, but larger impacts could have a worldwide effect on life on the Earth.

Nelson, 2004
Regional and Global Effects

Again, we as humans have no firsthand knowledge of what the effects of an impact of a large meteorite, asteroid or comet would be. Still, calculations can be made and scaled experiments can be conducted to estimate the effects. The general consensus is summarized here.

1.) There would be massive earthquakes - up to a Modified Richter Magnitude 13, and numerous large magnitude aftershocks would result from the impact of a large object with the Earth.

2.) The large quantities of dust put into the atmosphere from the impact would block incoming solar radiation. The dust could take months to settle back to the surface. Meanwhile, the Earth would be in a state of continual darkness, and temperatures would drop throughout the world, generating global winter-like conditions. A similar effect has been postulated for the aftermath of a nuclear war (termed a nuclear winter). Blockage of solar radiation would also diminish the ability of photosynthetic organisms, like plants, to photosynthesize. Since photosynthetic organisms are the base of the food chain, this would seriously disrupt all ecosystems. A graph of the projected global temperature is shown in the next slide if such an event occurred.

Nelson, 2004
The Estimated Global Temperature of Earth Over Time After a Major Space Object Impact

Regional and Global Effects - cont.

3.) Widespread wildfires ignited by radiation from the fireball as the object passed through the atmosphere would be generated. Smoke from these fires would further block solar radiation to enhance the cooling effect and further disrupt photosynthesis.

4.) If the impact occurred in the oceans, a large steam cloud would be produced by the sudden evaporation of the seawater. This water vapor and CO$_2$ would remain in the atmosphere long after the dust settles. Both of these gases are greenhouse gases which scatter solar radiation and create a warming effect. Thus, after the initial global cooling, the atmosphere would undergo global warming for many years after the impact.

5.) If the impact occurred in the oceans, giant tsunamis would be generated. For a 10 km-diameter object, the leading edge would hit the seafloor of the deep ocean basins before the top of the object had reached sea level. The tsunami from such an impact is estimated to produce waves from 1 to 3 km high! These could easily flood the interior of the continents.

6.) Large amounts of nitrogen oxides would result from combining Nitrogen and Oxygen in the atmosphere due to the shock produced by the impact. These nitrogen oxides would combine with water in the atmosphere to produce nitric acid which would fall back to the surface as acid rain, resulting in the acidification of surface waters. 

Nelson, 2004
The Frequency of Regional and Global Events

Although the odds are extremely small that Earth would be hit by a large asteroid or comet during a human lifetime, there would be a very large number of people killed if one occurred. Actuaries and astronomers have calculated/estimated the chances of death in different circumstances. See those results below.

### Frequency of Global Catastrophic Impacts

<table>
<thead>
<tr>
<th>Event Description</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. interval between impacts</td>
<td>500,000 yrs.</td>
</tr>
<tr>
<td>Annual probability a person will be killed</td>
<td>1/500,000</td>
</tr>
<tr>
<td>Assumed fatalities from impact</td>
<td>¼ of the human race!</td>
</tr>
<tr>
<td>Total ANNUAL probability of death</td>
<td>1/2,000,000</td>
</tr>
</tbody>
</table>

### Odds of Dying in the United States from Selected Causes

<table>
<thead>
<tr>
<th>Cause of Death</th>
<th>Odds of Happening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor vehicle accident</td>
<td>1 in 100</td>
</tr>
<tr>
<td>Murder</td>
<td>1 in 300</td>
</tr>
<tr>
<td>Fire</td>
<td>1 in 800</td>
</tr>
<tr>
<td>Firearms accident</td>
<td>1 in 2,500</td>
</tr>
<tr>
<td>Asteroid/Comet impact (lower limit)</td>
<td>1 in 3,000</td>
</tr>
<tr>
<td>Electrocution</td>
<td>1 in 5,000</td>
</tr>
<tr>
<td>Airplane crash</td>
<td>1 in 20,000</td>
</tr>
<tr>
<td>Flood</td>
<td>1 in 30,000</td>
</tr>
<tr>
<td>Tornado</td>
<td>1 in 60,000</td>
</tr>
<tr>
<td>Venomous bite or sting</td>
<td>1 in 100,000</td>
</tr>
<tr>
<td>Asteroid/Comet impact (upper limit)</td>
<td>1 in 250,000</td>
</tr>
<tr>
<td>Fireworks accident</td>
<td>1 in 1,000,000</td>
</tr>
<tr>
<td>Food poisoning by botulism</td>
<td>1 in 3,000,000</td>
</tr>
</tbody>
</table>

### Frequency of Impacts and Annual Risks of Death

For Tunguska-sized events:

<table>
<thead>
<tr>
<th>Event Description</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average interval between impacts</td>
<td>300 years</td>
</tr>
<tr>
<td>Average interval for populated areas only</td>
<td>3,000 years</td>
</tr>
<tr>
<td>Average interval for urban areas</td>
<td>100,000 years</td>
</tr>
<tr>
<td>Average interval for US urban areas only</td>
<td>1,000,000 years</td>
</tr>
<tr>
<td>Total annual probability of death</td>
<td>1/30,000,000</td>
</tr>
</tbody>
</table>

The Geologic Record of Mass Extinction

It has long been known (in the rock and fossil record) that the extinction of a large percentage of families or species of organisms have occurred at specific times in the history of our planet. Among the mechanisms that have been suggested to have caused these mass extinctions have been large volcanic eruptions, changes in climatic conditions, changes in sea level, and more recently, meteorite/comet/asteroid impacts.

The meteorite impact theory of mass extinctions has become accepted by many scientists for particular extinction events, but not all. Since there are many other possibilities for the cause of mass extinctions, please read your textbook for the arguments against the impact theory.

Nelson, 2004
The Rock and Fossil Record has shown major extinction events occurred at

- the end of the Tertiary Period, 1.6 million years (m.y.) ago.
- the end of the Cretaceous Period, marking the boundary between the Cretaceous and Tertiary periods 65 m.y. ago. (Geologists use the letter K to stand for Cretaceous Period and the letter T for the Tertiary Period. Thus this boundary is commonly called the K-T boundary).
- the end of the Triassic, 208 m.y. ago.
- the end of the Permian, 245 m.y. ago (estimated that over 96% of the species alive at the time became extinct).
- the end of the Devonian, 360 m.y. ago
- the end of Ordovician, 438 m.y. ago
- the end of the Cambrian period, 505 m.y. ago
The Mass Extinction at the end of the Mesozoic Era…

…that is the K-T boundary, 65 million years ago, shows much evidence that it was related to an impact with an extraterrestrial object. This event resulted in the extinction of over 50% of the species living at the time, including the dinosaurs. In 1978 a group of scientists led by Walter Alvarez of the University of California, Berkeley, were able to locate the K-T boundary very precisely in layers of limestones near Gubbio, Italy. At the boundary they found a thin clay layer. Chemical analysis of the clay revealed that it contains an anomalously high concentration of the rare element Iridium (Ir). Ir has extremely low concentrations in most crustal rocks, however it reaches very high concentrations in meteorites. The only other possible source of high concentrations of Ir is basaltic magmas. Over the next several years, the K-T boundary was located at several other sites throughout the world, and also found to have a thin clay layer with high concentrations of Ir. Although a large eruption of basaltic magma could not immediately be ruled out as the source of the high concentration of Ir, other evidence began to accumulate that the fallout of impact ejecta had been responsible for both the thin clay layers and the high concentrations of Ir. Among the evidence found at different localities where the K-T boundary is exposed is:

- Clay layers at some localities have a high proportion of black carbon that could have originated as soot produced by wildfires set off by an impact.
- Some of the clay layers contain grains of quartz with a crystal structure that shows evidence that the quartz was severely strained by a large shock.
- In some clay layers tiny grains of the mineral stishovite is found. Stishovite is a high pressure form of SiO$_2$ that is not found at the Earth's surface except around known meteorite impact sites. The mineral can only be produced as a result of extremely deep burial in the Earth, or by high pressure generated by an impact.
- Other clay layers contain tiny spherical droplets of glass, called spherules. The glass is not basaltic in composition, but could represent droplets of melt formed during an impact event.

Nelson, 2004
Although the crater itself is now filled and buried by younger rocks, drilling throughout the Gulf of Mexico has revealed the presence of shocked quartz, glass spherules, and soot in deposits the same age as the crater. In addition, geologists have found deposits from the tsunami that was generated by the impact all along the Gulf of Mexico coast extending considerable distance inland from the current shoreline. The size of the crater suggest that the object that produced it was about 10 km in diameter. While there is still some debate among geologists and palaeobiologists as to whether or not the extinctions that occurred at the K-T boundary were caused by the impact that formed Chicxulub Crater, it is clear that an impact did occur about 65 million years ago, and that it likely had effects that were global in scale. What would happen if another such event occurred while we humans dominate the surface of the Earth, and what could we as humans do, if anything to prevent such a catastrophic disaster?

The Chicxulub Impact Crater Site and the Probable Meteorite Path Before Impact
Recent Close Calls of Large Space Objects

- In March, 1989 an asteroid named 1989 FC passed within 700,000 km of the Earth, crossing the orbit of the Earth. It was not discovered until after it had passed through the orbit of the Earth. Its size was estimated to be about 0.5 km. Such a body is expected to hit the Earth about once every million years or so, and would release an energy equivalent to about 10,000 megatons of TNT, a little greater than the energy released in a nuclear war, and enough to cause nuclear winter event. Although 700,000 km seems like a long distance, it translates to a miss of the Earth by only a few hours at orbital velocities!

- On June 17, 2002 the LINEAR Spaceguard system discovered Near Earth Asteroid 2002 MN, which had passed the Earth on June 15 at a distance of only 120,000 km, one of the closest asteroid fly-bys on record. Based on its brightness, 2002 MN has a nominal diameter of about 100 m, large enough to penetrate through the atmosphere to the surface if it struck the Earth. In March, 2002, another asteroid, 2002 EM7, passed within 463,000 km. This asteroid also was not found until after its flyby of Earth.

- On March 19, 2004, a 30 m diameter asteroid, named 2004 FH, passed within 26,500 miles (43,000 km) of earth, just beyond the orbit of weather satellites. The object was small, and likely would have only caused a local effect if it had hit the earth's atmosphere, but it was discovered only 4 days before it passed!
Future Threats?

- Near-Earth Asteroid, *Apophis*, is the best current example of a possible future impactor. At approximately the size of two-and-a-half football fields, it would cause significant damage if impacting the Earth. Thankfully, recalculated orbits (as of October 7, 2009) suggest a minimal 1/250,000, or a .004%, impact chance of striking the Earth on Friday, April 13, 2036.
- However, when this asteroid was first discovered in 2004, initial estimates put it at a 2.7% chance of striking Earth on Friday, April 13, 2029. However, further research shows that it shouldn’t hit then, but rather come to about 18,000 miles from earth.
- There are further calculations that show another close pass by Apophis in 2068!

Brown, et. al, 2009

Morrison, 2006
An Asteroid and Comet Impact Scale

• The Torino Scale is a "Richter Scale" for categorizing the Earth impact hazard associated with newly discovered asteroids and comets. It is intended to serve as a communication tool for astronomers and the public to assess the seriousness of predictions of close encounters by asteroids and comets during the 21st century.

• The Torino Scale was created by Professor Richard P. Binzel in the Department of Earth, Atmospheric, and Planetary Sciences, at the Massachusetts Institute of Technology (MIT).

• A revised version of Binzel’s 1st version was presented at a June 1999 international conference on near-Earth objects held in Torino (Turin) Italy.

My visit with Dr. Binzel at M.I.T. in May of 2006.

Chaisson, et. al. 2008
### THE TORINO SCALE
Assessing Asteroid and Comet Impact Hazard Predictions in the 21st Century

<table>
<thead>
<tr>
<th>Events Having No Likely Consequences</th>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>The likelihood of a collision is zero, or well below the chance that a random object of the same size will strike the Earth within the next few decades. This designation also applies to any small object that, in the event of a collision, is unlikely to reach the Earth's surface intact.</td>
</tr>
<tr>
<td>Events Meriting Careful Monitoring</td>
<td>1</td>
<td>The chance of collision is extremely unlikely, about the same as a random object of the same size striking the Earth within the next few decades.</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>A somewhat close, but not unusual encounter. Collision is very unlikely.</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>A close encounter, with 1% or greater chance of a collision capable of causing localized destruction.</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>A close encounter, with 1% or greater chance of a collision capable of causing regional devastation.</td>
</tr>
<tr>
<td>Threatening Events</td>
<td>5</td>
<td>A close encounter, with a significant threat of a collision capable of causing regional devastation.</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>A close encounter, with a significant threat of a collision capable of causing a global catastrophe.</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>A close encounter, with an extremely significant threat of a collision capable of causing a global catastrophe.</td>
</tr>
<tr>
<td>Certain Collisions</td>
<td>8</td>
<td>A collision capable of causing localized destruction. Such events occur somewhere on Earth between once per 50 years and once per 1000 years.</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>A collision capable of causing regional devastation. Such events occur between once per 1000 years and once per 100,000 years.</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>A collision capable of causing a global climatic catastrophe. Such events occur once per 100,000 years, or less often.</td>
</tr>
</tbody>
</table>

Chaisson, et. al. 2008
Protecting Earth from Impacts

Impacts are perhaps the only natural hazard that we can prevent from happening by either deflecting the incoming object or destroying it. Of course, we must first know about such objects and their paths in order to give us sufficient warning to prepare a defense. Sufficient time is usually thought to be about 10 years. This would likely give us enough time to prepare a space mission to intercept the object and deflect its path by setting off a nuclear explosion. Although several tentative plans have been discussed (as of January 2009) to deflect or otherwise mitigate a threatening asteroid or comet, there have been no known efforts of creation or testing of these theories.

But, even if we did not have the ability to destroy or deflect such an object, 10 years warning would provide sufficient time to store food and supplies, and maybe even evacuate the area immediately surrounding the expected impact site.

The graph to the right shows that: “The longer the action time of a force applied to a NEO the lower is the energy required to move its impact point off the Earth and the larger is the NEO than can be so moved.” So, if a NEO of a diameter of 100 meters is expected to impact the earth in a few months, a large kinetic impact or a nuclear weapon would be needed to destroy it. But, if it was 5 years away from impact, an electric thruster or chemical thruster could be used to slow it down or speed up from colliding with the Earth.

Landing on a Comet or Asteroid; Is it Possible?

• In July of 2005, NASA’s *Deep Impact* (named after the 1998 movie about a Comet impacting with Earth) spacecraft, successfully landed on the Comet Tempel 1.
  – This mission was created to:
    1.) Further study comets.
    2.) Explore the possibilities of successfully landing on a fast moving object, in space.
  – The mission took 6 years from planning to landing.

• On May 9, 2003, the Japanese un-manned spacecraft *Hayabusa* (the Japanese word for “falcon”) was launched to observe and land on the asteroid *Itokawa*. It successfully landed in November 2005. The Hayabusa spacecraft is returning to Earth in June of 2010, hopefully with small samples (less than 1 gram) of *Itokawa* obtained when it touched down on the asteroid’s surface.

• The European Space Agency is directing the current Rosetta mission, which is due to orbit and land a probe on the comet 67P/Churyumov-Gerasimenko in 2014 for long term observations.

*Comet Tempel 1 and an oversized photo of Deep Impact next to it.*

*ESA - NEO - Don Quijote concept, 2010
Hayabusa, 2010
Bekey, 2009
NASA - Mission Overview, 2008*
Sources Cited