Astro 102/104 Our Solar System **Spring 2008**

NAME:_______Solutions ____________________ Section Number:_______________

Homework 9: Comets, Impacts and Jupiter

Due: in your section on **the week of April 7th**. Be neat and concise, show your work, and remember units. An answer without the correct units is wrong.

Suggested reading: Lecture notes 24, 25, and 26, and chapters 12, 7.1, and 11.1.

1. [2 Points] The comet Shoemaker-Levy 9 was captured into orbit around Jupiter sometime in the 1960s or 1970s and in 1992, it passed so close to Jupiter (just 40,000 km above the cloud-tops) that the giant planet's powerful tides tore it apart into about 20 large pieces. If the comet's original nucleus was a 5km diameter sphere of water ice, how much mass (on average) do the large pieces have?

   To calculate the mass of the original nucleus, use the volume of a sphere and the given density. To be strictly correct, use the density of water ice: 920 kg/m³

   Mass =Volume x Density $= 4/3\ \pi R^3 \rho = 4/3\ \pi\ (2500\ m)^3\ (920\ kg/m^3) = 6.02 \times 10^{13}\ kg$

   Assuming that this mass is divided into 20 equal pieces, each piece would have a mass of 3.01×10^{12} *kg.*

   Alternatively, to get an approximate value, you could just use the density of water. This will slightly overestimate the mass:

   Mass = Volume x Density $= 4/3\ \pi R^3 \rho = 4/3\ \pi\ (2500\ m)^3\ (1000\ kg/m^3) = 6.54 \times 10^{13}\ kg$

   This gives a mass of 3.27×10^{12} *kg for each of the 20 pieces.*

2. [4 Points] Jupiter has a mass of 1.899×10^{27} kg, and a radius of 71,492 km at the equator. What is Jupiter's escape velocity in kilometers per second? What is the minimum velocity with which something can impact Jupiter in kilometers per second? (ignore the planet's orbital velocity) Explain the relationship between the escape velocity and the minimum impact velocity.

   The equation for escape velocity is:

   $v_{esc} = (2GM/r)^{1/2}$

   For Jupiter, $v_{esc} = (2 * 6.67 \times 10^{-11}\ m^3 kg^{-1} s^{-2} * 1.899 \times 10^{27}\ kg / 7.15 \times 10^7\ m)^{1/2} = 59{,}500\ m/s = 59.5\ km/s$

   The escape velocity is the speed at which something needs to travel so that it can escape the *gravitational influence of another object in space. If something starts on the surface of a planet traveling at the escape velocity, it will continue out into space, always slowing down, as its initial kinetic energy is converted into potential energy. Finally, when it is "infinitely" far away it will have zero velocity and all of its initial energy will be stored as potential energy.*

Now, consider the exact opposite scenario: a comet begins very far away with almost zero kinetic energy and begins to fall toward a planet. As it falls, its potential energy is converted into kinetic energy until, when it reaches the surface, its energy is all kinetic. This is the reverse of the scenario described above for the escape velocity.

The bottom line: an object starting at a low velocity and falling from very far away will hit the surface of a planet at that planet's escape velocity.

This means that ***the minimum impact speed is the escape velocity****!*

3. [3 Points] The fragments of Shoemaker-Levy 9 impacted Jupiter in July of 1994 with a velocity of roughly 60 km/s. How much energy was released in each impact, on average? How much total energy was released? How does this compare to the amount of energy that would be released if the world's entire arsenal of nuclear weapons (~10,000 Mt) were detonated? Express your answers in Megatons of TNT (1 Mt = 4.2×10^{15} J)

   The energy of each impact is given by the kinetic energy equation. Use the mass calculated in problem #1 and the impact velocity given:

   $E = \frac{1}{2} mv^2 = \frac{1}{2} (3.01 \times 10^{12} \text{ kg}) (60{,}000 \text{ m/s})^2 = 5.42 \times 10^{21}$ *joules* = 1.29×10^6 *Mt = 129 times the world's nuclear arsenal!*

   Total energy released by the combined impacts of all 20 fragments: 2.58×10^7 *Mt = 2580 times the world's nuclear arsenal!*

   If you used the density of water in problem #1 instead of ice, the corresponding energies are: 5.89×10^{21} *J* (1.4×10^6 *Mt) for each fragment and* 1.17×10^{23} *J* (2.8×10^7 *Mt) total.*

4. [2 Points] Briefly describe the possible effects if a comet with the same energy as Shoemaker-Levy 9 (the whole thing, not just one fragment) impacted the Earth.

   An impact with the same energy as the Shoemaker-Levy 9 impact would be a global catastrophe. The impact itself would instantly destroy anything within a few hundred kilometers and would trigger earthquakes and tsunamis (particularly if the impact occurred in the ocean) with wider-ranging damage. Debris thrown up into space by the impact would rain down around the world, possibly triggering a "global firestorm".

   Smoke and dust from the impact and the resulting fires would block out the sun, possibly for years, causing the extinction of many plants and phytoplankton that form the foundation of most food chains. The resulting collapse of food chains would result in the extinction of many species.

The impact might also create large amounts of NO_2 in the atmosphere. NO_2 is a poisonous reddish gas which would color the sky red and contribute to blocking the sun and shutting down photosynthesis.

Widespread fires would also add a tremendous amount of CO2 to the atmosphere, triggering a temporary enhanced greenhouse effect once the dust cloud settled.

Another possible result of a large impact of this type is global acid rain, which could be devastating to vegetation and plankton with carbonate shells which would dissolve.

All in all, Earth would not be a very pleasant place for a while after an impact of this magnitude.

5. [2 Points] The rate of impacts with Jupiter is thought to be several thousand times the rate of impacts with the Earth. With this information and your answer to question #4 in mind, is Jupiter's presence in the outer solar system beneficial or detrimental to life on Earth? Explain why.

   Jupiter's powerful gravitational pull means that it intercepts many comets before they reach the inner solar system. Comets that interact with Jupiter often either are thrown out of the solar system, or are captured by Jupiter and eventually collide with it. Thus, the presence of Jupiter tends to reduce the number of comets that reach the inner solar system, and therefore reduces the frequency of catastrophic impacts. Some scientists have even made the claim that, without Jupiter to protect the earth and reduce the frequency of impacts, complex life would not have had time to develop before it was wiped out.

6. a) [5 Points] Jupiter emits 1.8 times as much energy as it receives from the sun. If the planet has an albedo of about 0.5, and is about 5.2 AU from the sun, how much energy must be generated inside the planet for the following energy balance equation to hold true? The sun gives off 3.83×10^{26} Joules of energy every second.

   Solar Energy + Internal Energy = Emitted Energy

   Note: This equation should technically be in terms of power, not energy. It is assumed throughout the solution that all energies are "per second".

   Solar Energy per second = [Energy per second per square meter at Jupiter] x (Jupiter's cross sectional area) x (Fraction of energy absorbed)

   $$= [L_{sun}/(4\pi r^2)]\ (\pi R_{Jup}^2)(1-A)$$

   $$= \underbrace{[(3.83\times10^{26}\ J/s)\ /\ (4\ \pi(5.2\ AU \times 1.50\times10^{11}\ m/AU)^2)]}_{\text{Solar ``Constant'' at Jupiter}}\ (\pi\ (7.15\times10^{7}\ m)^2)(1-0.5)$$

   $$= 4.02 \times 10^{17}\ J/s$$

Internal Energy (per second) = Emitted Energy (per second) – Solar Energy (per second)

*Internal Energy (per second) = 1.8 * Solar Energy(per second) – Solar Energy(per second) = 0.8 * Solar Energy =* 3.22×10^{17} *J/s*

b) [2 Points] What is the source of this internal energy?

Jupiter releases excess internal energy because the planet is still in the process of contracting, even 4.5 billion years after its formation! When Jupiter was formed it was about twice its current size and was much hotter. It has since cooled and contracted, and continues to shrink by ~2cm per year! As it contracts, gravitational potential energy is turned into heat, which is observed as excess infrared emission.