Calculate the average density of the Milky Way Galaxy

Detailed Response to the caught zomb from *poly*
As described at www.zombal.com
Report by *dragozzine*
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Zomb Statement:

The task is to calculate the average density of the Galaxy, using the following assumptions. First, find the average distances of the 6 nearest major galaxies to the Milky Way, and assume the Galaxy occupies a sphere of diameter half this average distance. Assume a galaxy is 'major' if its mass is greater than 50% of the Milky Way, otherwise minor.
Find figures for the mass of the Galaxy (including central black hole and minor/ satellite galaxies within the sphere) and any other matter amounting to more than 0.01% of this.
Divide the mass by the volume to get density (in gm per cubic centimetre).

Response

Abstract: The mass, size, and volume of the Milky Way Galaxy aren't exactly known. Furthermore, there are multiple different meaningful ways to calculate the density of a non-uniform distribution. After giving some brief background, I have followed the described method to find an average density of 10^{-29} g/cc (grams per cubic centimeter). Due to the unknown amounts of matter, even in our own Galaxy and especially in other galaxies, this number is uncertain to within about an order of magnitude, i.e., 10^{-28} to 10^{-30} g/cc are all possible. Other methods for defining the density give different answers as well. Different definitions of where you draw the line for what defines the volume of the Galaxy can give very different answers ranging from 10^{-23} to 10^{-30}, as described herein.

To determine the average density of the galaxy, we must estimate it's mass and volume.

Background

Based on modern-day cosmology, the universe started as a homogeneous medium, with two main sources of gravitational forces: dark matter and "regular" baryonic matter (protons, neutrons, planets, stars, people, etc.). While the nature of dark matter is unknown[1], it dominates over baryonic matter by a factor of about 5 based on several lines of evidence.

Small perturbations in the early universe along with the always-attractive nature of gravitational interactions have caused the initial material to collapse into a "cosmic web" of dark matter filaments, where galaxies (repositories of baryonic matter) tend to sit at the higher-density intersections of filaments.[2] The organization of material is hierarchical, almost fractal. Our Galaxy is the dominant member of the Milky Way subgroup, which is part of the "Local Group" of Galaxies (including Andromeda Galaxy, with which the Milky Way form something like a "galactic binary"), which is a part of the Virgo Supercluster. (One of my favorite visualizations of the scale of the universe that shows some of these relationships is here: http://htwins.net/scale2/ .) Throughout, we'll be working in units of parsecs (and kiloparsecs and Megaparsecs, kpc, Mpc), where 1 pc = 3.086×10^{18} centimeters. (We'll

1 One leading theory is massive weakly interacting atomic-scale particles. Various observational studies have ruled out the possibility that it is stars, planets, black holes, or other "compact massive objects". Still, the nature of dark matter remains unknown.

2 I am oversimplifying immensely topics such as dark matter halos, galaxy formation and evolution, large scale structure, etc., etc., that could easily take an entire semester to cover the basics of the modern theories.

also be working with the American English spelling of centimeter. :))

Volume

Gravitational interactions have highly amplified the small perturbations of the early universe, creating a very heterogeneous distribution of matter and dark matter. Therefore, there are multiple conceivable ways in estimating the volume of the Milky Way.

The Milky Way, like most spiral galaxies, has three dominant components: the disk, the bulge, and the halo. The disk is where the vast majority of luminous stars are and is what you see in a pretty picture of a galaxy.

The standard method notices that the Milky Way disk has a moderately clear "edge" where the stellar density drops rapidly (although it's not a true edge as there are stars further out), so that the disk of the has a radius of about 16 kpc and a height of about 0.3 kpc. The halo has a radius of about 30 kpc and mostly contains globular clusters. The bulge is an excess density of stars and matter near the center of the Galaxy that is larger than the thickness of the disk, but much smaller than the halo.

So, there are a couple of possible Volume measurements here
Disk volume = 241 kpc^3
Halo volume = 113000 kpc^3

The Zomb recommends that we consider the distance to satellite galaxies in our accounting.
http://en.wikipedia.org/wiki/List_of_Milky_Way%27s_satellite_galaxies

However, what counts as a "major" satellite galaxy is tricky. The Zomb recommends using a mass threshold that if the satellite galaxy is 50% of the Milky Way's mass, then it counts as a major galaxy. However, none of the traditional satellite galaxies are so large, Wikipedia gives the mass of the largest satellite galaxy to be only 1% of the Milky Way's mass (see more below). Thus the nearest "major" galaxy in this definition would be the Andromeda Galaxy which has a mass comparable to (or perhaps larger) the Milky Way. It lies at a distance of 800 kpc (with non-negligible error). That corresponds to a volume of 2.1 billion kpc^3, a huge difference from the standard volume from the halo.

Using estimated absolute magnitude as a proxy for mass, "major" galaxies are those with an absolute magnitude less than about -20 (Milky Way has -20.8, LMC has -18, Andromeda -21.5, for example). Using: http://en.wikipedia.org/wiki/List_of_nearest_galaxies
we have as the closest major galaxies: Andromeda, NGC 55+NGC 300, Maffei/IC 342, and others.
In actuality, these galaxies each have ~dozens of satellite galaxies and form their own groups, like the Milky Way's Local Group. Using: http://en.wikipedia.org/wiki/List_of_galaxy_clusters
we can find the 6 nearest groups:
LGG 104/IC 342/Maffei, M81, Centaurus A/M83, Sculptor, Canes Venatici, and NGC 1023.

So, we might say that an interesting volume is the volume of the local group, defined as the half distance to the nearest local group, LGG 104/IC 342/Maffei at 3 Mpc. That gives a volume of 14 billion kpc^3.

Finally, the volume directly specified by the Zomb would be the distance to the 6^{th} closest major galaxy, which is effectively the distance to the 6^{th} closest local group (including our own group), i.e., about 4 Mpc, giving a volume of 268 billion kpc^3.

The large differences between these estimates are due to the hierarchical nature of the matter clustering on scales larger than a galaxy.

Mass of the Milky Way
While dark matter dominates the universe, it's distribution within and around the Milky Way is more complicated. It's thought to be more diffuse than the visible matter, so that the disk is actually mostly baryonic mass. The disk+bulge mass of the Milky Way has a wide variety of estimates, but a commonly used estimate is 50 billion solar masses (Binney & Tremaine).

When you go out to much larger distances, you encapsulate the galactic halo and a lot more dark matter.
http://adsabs.harvard.edu/abs/2010MNRAS.406..264W
give a Milky Way mass of just over a trillion solar masses, with significant uncertainties, within the nearest 300 kpc, which is a pretty typical measurement.

Small contributors like the supermassive black hole at the galactic center (a few million solar masses) and even the dwarf galaxies nearby: the largest of these is the Large Magellanic Cloud which is thought to have a mass of only 1% of the Milky Way (tens of billions of solar masses).

The mass of the whole local group is thought to be also about a trillion solar masses:
http://www.springerlink.com/content/r774717g00111425/
the only other major source of mass is the Andromeda Galaxy. So, we'll say 2 trillion solar masses.

The masses of other local groups are not obvious, but the M81 group is estimated to be about the same mass as the local group. So, we'll say that this mass is about 10 trillion solar masses total.

Density Estimates:
Using the attached spreadsheet, we can convert these masses and volumes into densities in g/cc.
Density of disk = 5*10^10 solar masses / 241 cubic kpc
Density of Milky Way + Halo: 10^12 solar masses / 113000 cubic kpc
Density of Milky Way out to Andromeda: 10^12 solar masses / 2.1 billion cubic kpc
Density of Local Group: 2*10^12 solar masses / 14 billion cubic kpc
Density of region containing nearest 6 local groups: 10^13 solar masses / 268 billion cubic kpc

These give densities in solar masses per cubic parsec of about 0.2, 0.01, 0.000001, 0.0000001, and 0.00000003, respectively. This is to be compared with the typical average density near the Sun, which is usually given at 0.1 solar masses per cubic parsec; since the Sun is within the Milky Way disk, it is unsurprising that these densities are similar.

Okay, now to the densities in g/cc. More specific numbers are given in the spreadsheet, but to emphasize our uncertainties in these estimates, here I only list the order of magnitude:

Milky Way Disk	**10^{-23} g/cc**
Milky Way Halo	**10^{-26} g/cc**
Milky Way to Andromeda	**10^{-29} g/cc**
Local Group	**10^{-29} g/cc**
Nearest Local Groups	**10^{-30} g/cc**

These can also be interestingly compared to the average density of the universe which is also 10^{-29} g/cc.

I believe that the above answers the questions posed in this Zomb, along with given significant explanation. Please let me know if any of the above arguments are unclear or if you have any other questions or zombs. Doing a Google or Wikipedia search on most of the above concepts will provide helpful insights and references. Other bibliographic citations are available upon request.

Thank you for this opportunity.

Dr. Ragozzine is a Postdoctoral Researcher in the Astronomy Department at the University of Florida. He is currently funded by the United States National Aeronautics and Space Administration (NASA) to work on the NASA Kepler Space Mission. This document is his personal composition and reflects his personal opinion, not that of the University of Florida, NASA, or any other party. He has many years of research experience in the orbital dynamics of planetary systems, the Kuiper belt within our own solar system, and extra-solar planets observed around other stars.