The New Cosmology

I. The Scale of Things

Cosmology is the study of the physical structure and evolution of the Universe as a whole. That's a BIG subject! In some sense the biggest subject of them all. To be able to ever wrap our minds around it we need to ease into it rather gently at first and get exposed to the enormous scale of the subject in small steps. Eventually we'll be talking right and left of one thing being a hundred million or several billion times as large as another thing, but, even in today's economies and government deficits such numbers feel rather meaningless in an abrupt encounter. So we start small.

1. The Earth and The Moon: My guess is that the reader has traveled in a commercial jet liner at least once. If so, and especially if we fold in auto travel over interstate highways as well, then we've all traveled thousands of miles. Consequently, we all have a "feeling" for distances of a few thousand miles. It may not be a precise "feeling", but it gives us a rough sense of what such a distance is like; the notion of a thousand miles is not intimidating and it is not mind blowingly meaningless. That's good. Because a line from one side of the Earth to the other, which passes through the center, i.e., a **diameter** of the Earth, is about 8,000 miles long. I say it's *about* 8,000 miles long, not just because it's not *exactly* that long, but also because the length of the line depends on where it is. A diameter from one point on the equator to the opposite equatorial point is longer than the diameter from the South Pole to the North Pole. That's because the Earth's spinning motion tends to flatten the Poles a bit and expand the equator a little. But 8,000 miles is a good rough figure for the Earth's diameter.

But, of course, when we travel we don't go through the Earth! We go along it, or around it. For global travelers that makes the **circumference** of the Earth important. The circumference of the Earth is about 25,000 miles long, i.e., about 3 and 1/7 times the diameter. Since the Earth spins (we think of it as turning slowly) on its axis once every 24 hrs, this means that equatorial residents are zipping around the Earths center at better than 1,000 miles per hour, i.e.,

$$25{,}000 \text{ mi.} / 24 \text{ hr.} \;\geq\; 1{,}000 \text{ mi./hr. !}$$

If that never occurred to you before you might wonder why our friends in the tropics don't lift right up off the ground and fly away. Well, Earth's gravity is more than up to the task of holding them down – but they do tip their bathroom scales just a tad more lightly than their polar cousins – not only because some of gravity's force is used up just keeping them on the ground but also because they're slightly farther from Earth's center than their polar cousins. The differences are a fraction of a percent.

Taken by themselves, the Earth's diameter and the Earth's circumference are accidental numbers. They are what they are but, as far as anybody knows, they could have been otherwise. But their *relationship* is not accidental. The Earth, like the other planets, like the Moon, like the Sun and the stars is roughly a sphere, and on any sphere the relationship between a diameter and a circumference is the same as for a circle. The circumference, C, of a circle is proportional to the diameter, D, of the circle and the proportionality constant is the famous number called π and equal to 3.14159 - - - (an endless, non-repeating, decimal),i.e.,

$$(3+1/8)D < C = \pi D \sim 3.14 \times D \leq (3+1/7)D.$$

Since in Cosmology, as in Astronomy, one has many occasions to talk about circles, we will see this equation again. Sometimes we will refer to the **radius**, R, of the circle instead of the diameter, D. Since D = 2 R, the circumference, C, is related to the radius by,

$$C = 2 \pi R .$$

After the Sun, the Moon is the largest and most prominent object in our sky by far. How large it looks depends, of course, on how large it *is* and how far away it is. It turns out that the Moon is roughly 2200 mi. across and 240,000 mi. away. While that's still expressed in thousands of miles, the number is getting a little large and may make some people queasy. If so, think of it this

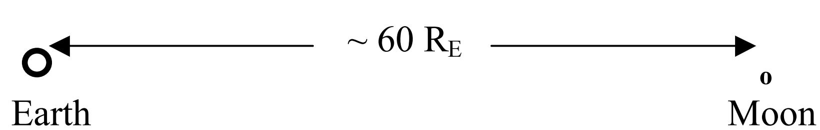

Fig. I.1: Rough picture of relative sizes and distance for the Earth – Moon system.

way, the Moon's distance is less than ten trips around the Earth. Or, another way, the Moon's distance is about 30 Earth diameters or 60 Earth radii (**Fig. I.1**).

Notice that since the Moon is about 60 times as far from the center of the Earth as we are, the circumference of its orbit must be about 60 times the circumference of the Earth. But since the Moon takes only about 28 days to go around the Earth, it completes its circumferential journey in only 28 times the time it takes our equatorial cousins. That means the Moon's speed in going around the Earth is about 60/28 times the speed of our equatorial cousins, or about 2,100 mi./hr.

2. The Sun: As we all know, the Sun is much farther away and much bigger than the Moon, about 93 million miles away. But that's one of those numbers that's hard to wrap your mind around. Since the Moon is a bit less than a quarter of a million miles away, a more digestible way to put it is that the Sun is a bit more than 4 x 93 = 372 times as far away as the Moon. More accurately it's about

$$(93{,}000{,}000 / 240{,}000) = (9{,}300 / 24) = (3{,}100 / 8) = (1{,}550 / 4) = (775 / 2)$$

$$= 388 \sim 390$$

times the Moon's distance (**Fig. I.2**). Since 10 circumnavigations of the Earth is close to a quarter million miles, the Sun is close to 3900 circumnavigations of the Earth away.

It's just a remarkable coincidence, but the Sun is also very close to 390 times as large as the Moon. That the ratio of the distances to the Sun and the Moon is the same as the ratio of their diameters, i.e.,

$$(d_{SE} / d_{ME}) = (D_S / D_M) , \qquad \text{or,} \qquad (D_S/d_{SE}) = (D_M/d_{ME}),$$

has been known for a very long time since we can see that in a total solar eclipse the Moon just exactly blots out the full disk of the Sun, not more and not less (**Fig. I.3**).

This makes the Sun about 110 times larger (in diameter) than the Earth. And this in turn means that the Sun's diameter is about 1 and 4/5 as large as the diameter of the Moon's orbit around the Earth (**Fig. I.4**), i.e.,

$$D_S \sim 390\ D_M \sim 110\ D_E \sim (9/5)\ 2\ d_{ME}$$

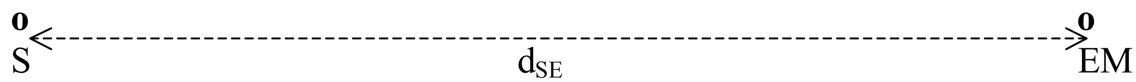

Fig. I.2: Sizes (small **o**) and distance between the Sun and the Earth-Moon system (roughly to scale).

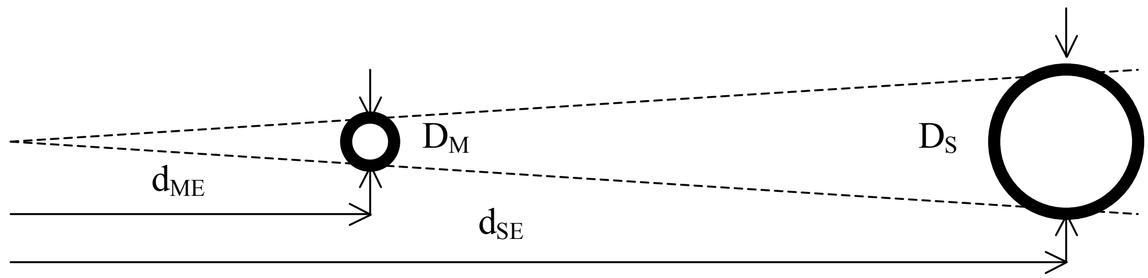

Fig. I.3: Total eclipse evidence of equal distance and diameter ratios (not to scale).

The circumference of the Earth's orbit around the Sun, with d_{SE} as the radius of the orbit, is close to

$$C_{ES} \sim 2\ \pi\ d_{SE} \sim 390\ (2\ \pi\ d_{ME}) \sim 390\ C_{ME}\ ,$$

where the first and last ~ signs are due to the Earth and Moon orbits not being perfect circles but slightly elongated elipses. Since the Earth takes about 365 days to orbit the Sun, the Earth's average speed around the Sun is

$$v_{ES} \sim (C_{ES}\ /\ 365\ \text{days}) \sim (390\ /\ 13)(C_{ME}\ /\ 28\ \text{days}) \sim 30\ v_{ME} \sim 63{,}000\ \text{mi./hr.}$$

We're all, equatorial and polar residents alike, *really* clipping along around the Sun!

When we move on to the planets of our solar system it will be convenient to express their distances from the Sun in terms of the Earth's distance. For that purpose astronomers introduce the Earth-Sun distance as a unit and call it

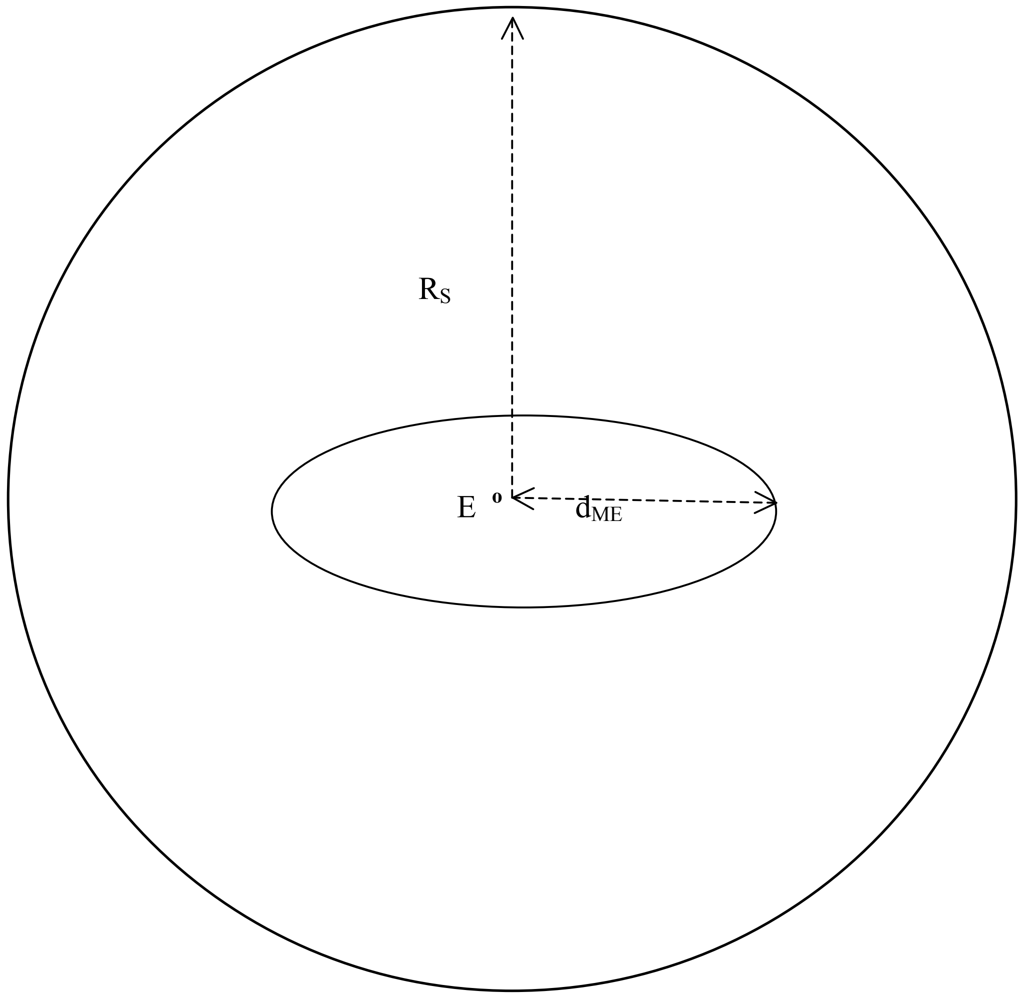

Fig. I.4: The Earth-Moon system placed inside the Sun (roughly to scale).

1 AU or **1 Astronomical Unit**. As we move out of our solar system and try to grasp the distances to stars even the AU will become too small for convenience. We then turn to distances covered by the speed champion of the Universe, light, in various amounts of time. The speed of light in vacuum is about 186,000 mi./sec. Consequently it takes a pulse of light about 1.3 sec. to travel from the Earth to the Moon and that distance, d_{ME}, is said to be about 1.3 light-seconds or 1.3 lgt.sec. It takes light about

$$(93{,}000{,}000 \text{ mi.} / (186{,}000 \text{ mi./sec.})) = 500 \text{ sec.} \sim 8.3 \text{ min.}$$

to reach the Earth from the Sun and so the distance, d_{SE}, is about 500 lgt.sec. or 8.3 light minutes (lgt.min.), i.e.,

$$d_{SE} = 1\ \text{AU} \sim 93{,}000{,}000\ \text{mi.} \sim 500\ \text{lgt.sec.} \sim 8.3\ \text{lgt.min.}$$

3. The Planets: Now we undertake to grasp the dimensions of our solar system, the next step on our way to the stars and galaxies. We begin with a simple list of the average distances of the planets from the Sun and the time they take to orbit the Sun (period). For easy comparison with the Earth we express the distances and times in terms of AU's and years, respectively.

Mercury: $d_{MeS} \sim 0.38$ AU , $T_{MeS} \sim 0.24$ yr.

Venus: $d_{VS} \sim 0.72$ AU , $T_{VS} \sim 0.62$ yr.

Earth: $d_{ES} \sim 1.00$ AU , $T_{ES} \sim 1.00$ yr.

Mars: $d_{MS} \sim 1.52$ AU , $T_{MS} \sim 1.88$ yr.

Jupiter: $d_{JS} \sim 5.20$ AU , $T_{JS} \sim 11.9$ yr.

Saturn: $d_{SS} \sim 9.54$ AU , $T_{SS} \sim 29.4$ yr.

Uranus: $d_{US} \sim 19.2$ AU , $T_{US} \sim 84.0$ yr.

Neptune: $d_{NS} \sim 30.1$ AU , $T_{NS} \sim 165$ yr.

[Pluto: $d_{PS} \sim 39.5$ AU , $T_{PS} \sim 248$ yr.]* Ooops! Pluto shouldn't be here any more.

Because of the sizeable jump that occurs when we move from Mars to Jupiter, the former is regarded as belonging to the *inner solar system* and the latter as belonging to the *outer solar system*. The range of the orbital radii in the solar system is expressed by the factor of about 100 between [Pluto's]* distance from the Sun and Mercury's. An interesting coincidence, so far as we know, is that it is these two extreme planetary orbits, the largest and the smallest, that are the most elliptical by far. For a small portion of [Pluto's]* 248 year long orbit it is actually slightly closer to the Sun than Neptune and then, 124 years later, it ranges close to 50 AU away from the Sun. Similarly, but much more quickly, Mercury gets about as close as 0.28 AU to the Sun and then, 44 days later, is about 0.48 AU away.

Notwithstanding the wide ranges in these data, the solar system is, definitely, a *system*; as **Johannes Kepler** discovered in the early 1600's when he found that, for the six planets then known, the quantity,

$$(d^3/T^2) = \text{(average distance from the Sun)}^3 / \text{(period)}^2$$

had roughly the same value for each planet. That value is clearly about 1 $AU^3/yr.^2$, since that is the value for the Earth, and it holds for all nine planets. Kepler thought this remarkable fact was a manifestation of divine design and the harmony of the heavens. But ever since **Newton** in the late 1600's it has been interpreted as a consequence of the motion of all the planets being dominated by the strong gravity of the Sun.

Notice that it would take a light pulse from the Sun about

$$39.5 \text{ x } 8.3 \text{ min.} \sim 5.5 \text{ hr.}$$

to reach the average distance to [Pluto]*. So from one side of the solar system to the opposite side is ~ 79 AU ~ 11 lgt. hr. in distance (**Fig. I.5**).

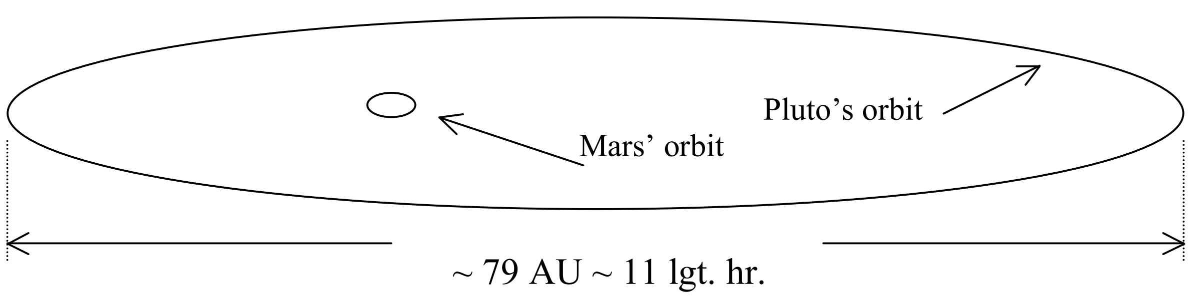

Fig. I.5: The boundaries of the inner and outer solar system; the orbits of Mars and Pluto (portrayed somewhat edge on and roughly to scale).

4. Comets, the Kuiper Belt and the Oort Cloud: For some time now the comets that have been observed in the solar system have been placed in two distinct classes; the short period comets or SPCs and the long period comets or LPCs. The most famous SPC is **Halley's Comet** that returns to the Sun's neighborhood every 76 years. LPC comets (of which the **Hale-Bopp** comet is the best known) have orbital periods greater than about 200 years and, usually, have extremely elongated orbits.

But even more striking than the orbital period differences of the two types of comets is the assessment of where they come from.

The SPCs tend to have orbits that lie in or near the general plane of the planetary orbits (only [Pluto]* has an orbital tilt that lies noticeably out of the general plane) and their greatest orbital distances from the Sun tend to lie between 30 AU and 100 AU. This region, starting at about Neptune's orbit, defines the **Kuiper Belt**, a conjectured region of smallish rocky and icy debris that seems to be the origin of the SPCs which get sent into the inner solar system by collisions or gravitational disturbances. Only in the 90s did we acquire some *direct* observational evidence of its existence.

The LPCs, on the other hand, seem to come from all possible directions indiscriminately, as **Jan Oort** discovered in 1950 as a result of a statistical survey of the data. He also found that the LPC orbits had maximum orbital distances at about 50,000 AU! He conjectured the existence of a vast spherical cloud of rocky and icy debris as the source of the LPCs. This cloud is called the **Oort Cloud**. But 50,000 AU is so far away for such small objects as comets (which have no glowing tails at that distance) that no direct observational evidence of its existence has ever been obtained. Still, most astronomers believe it exists and many think it contains enough material to have as much mass as Jupiter. If so, this cloud appears to define the very outermost limits of the dominant gravitational influence of the Sun and solar system. Since

50,000 x 8.3 min = 415,000 min. ~ 6,900 hr. ~ 290 days ~ 0.79 yr.,

it follows that the diameter of the Oort Cloud is about 1.6 lgt.yr. (**Fig. I.6**).

5. The Nearest Stars: Let's recapitulate a bit. Essentially, we first went from the length of the Earth's diameter to the distance to the Moon, a jump by a factor of about 30. Then from the Moon's distance we jumped to the Sun's distance, an additional factor of about 390. Then through the solar system proper to the orbital radius of the farthest planet, [Pluto]*, an additional

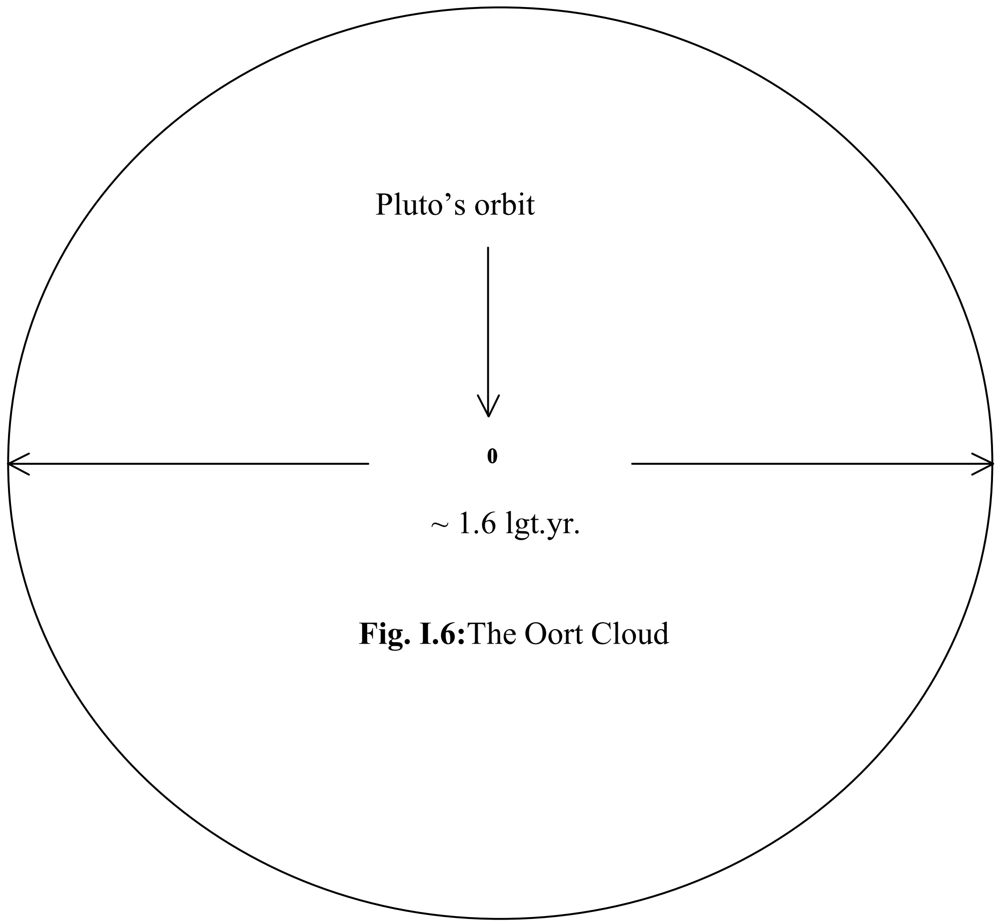

Fig. I.6: The Oort Cloud

factor of about 40. And, lastly, from Pluto's orbital radius to the distance from the Sun to the Oort Cloud, a big jump by a factor between 1200 and 1300. In other words the distance to the Oort cloud is about

$$30 \times 390 \times 40 \times 1200 \sim 560{,}000{,}000$$

times the diameter of the Earth!!

Our next jump, to the nearest star, **Alpha Centauri**, is a small one, for Alpha Centauri is only about 5.6 times farther away than the Oort cloud, i.e.,

$$d_{\alpha C} \sim 4.4 \text{ lgt.yr.} \sim 5.6 \times 0.79 \text{ lgt. yr.}$$

This is the third brightest star in the sky but it can only be seen South of the 30^0 North latitude in the constellation of the Centaur. It's actually a double star system with the stars orbiting each other a little closer than the Sun and Neptune.

We know of 20 stars that are within about 12 lgt.yr. of the Sun. **Sirius**, the dog star in the constellation **Canis Major** and the brightest star in the sky (best seen in February), is 8.6 lgt.yr. away. **Procyon**, the eighth brightest star in the sky, in the constellation of **Canis Minor**, is about 11 lgt.yr. away. But brightness is no reliable indicator of distance. The second brightest star, **Canopus**, is 74 lgt.yr. away. It's just a very bright star! As we consider larger and larger distances the number of stars increases rapidly. This makes sense since if the stars were distributed uniformly through space their number should increase as the cube of the distance, i.e., for every doubling of the distance we should find about 2 x 2 x 2 = 8 times as many stars within that distance. This last thought gives rise to the famous **Olber's Paradox** about why the night sky is dark (see the **Appendix**).

Ever since we considered the Oort cloud we've been dealing with objects the distance of which forces us to consider the time delay in what we're seeing. An observer in the Oort cloud would, at any time, see Sunlight that had been emitted over nine months before. We see Alpha Centauri as it was 4.4 years ago. If that star exploded now we wouldn't know it for 4.4 years. Quite generally, the farther away stellar objects are, the farther into their past do our present observations of them probe. In our common experience the closest analogue to this feature is the delay in hearing the thunder emitted by a distant lightning bolt. The light from the lightning arrives instantaneously (If the bolt occurs a mile away it takes the light it emits only about ten millionths of a second to reach us) while the sound may take several seconds to arrive. We can even notice the delay in the sound made by a distant axe or hammer compared to when we see it strike. The main differences in the case of stellar objects is that, first, since nothing moves through space faster than light (so far as we know) we only receive the delayed signal without anything else to play the role of an instantaneous indicator, and second, the delays are quite long and, as we will see, can be enormous.

6. The Milky Way: On a clear night humans have, since ancient times, noticed the oddly cloud-like mildly luminous band that lays across the sky. Many ancient myths construed this band as a stream or river for divine vessels. We call it the **Milky Way** from the Greek word "**galaxy**" which means milk. While many stars are scattered in front of the band, the band itself is not obviously starry to the naked eye. But a modest telescope immediately reveals the vast multitude of dim stars that comprise the band. Taken at face value the distribution of faint stars in the Milky Way violates the notion that stars are distributed roughly uniformly throughout the sky and this immediately raises the question, why?

For many years most astronomers thought the Milky Way contained almost all the stars of the Universe in a roughly **oblate ellipsoid** with our Solar System roughly in the middle.

We now 'know' that the concentrated band of stars is the part we can easily see of a vast collection of stars, the Milky Way Galaxy, to which our Solar System, Oort Cloud and all, belongs, *along with an estimated 100 billion other stars*! We are not at the center of the Galaxy but about 27,000 lgt. yrs. from the center, in the large disc-like portion of the Galaxy which has a diameter of about 110,000 lgt. yrs. and, at the Sun's location, is about 1000 lgt. yrs. thick! Like essentially all the other stars in the disc, our Sun orbits the star filled, central spherical bulge of the Galaxy which has a radius of about 12,500 lgt. yrs (**Fig. I.7**).

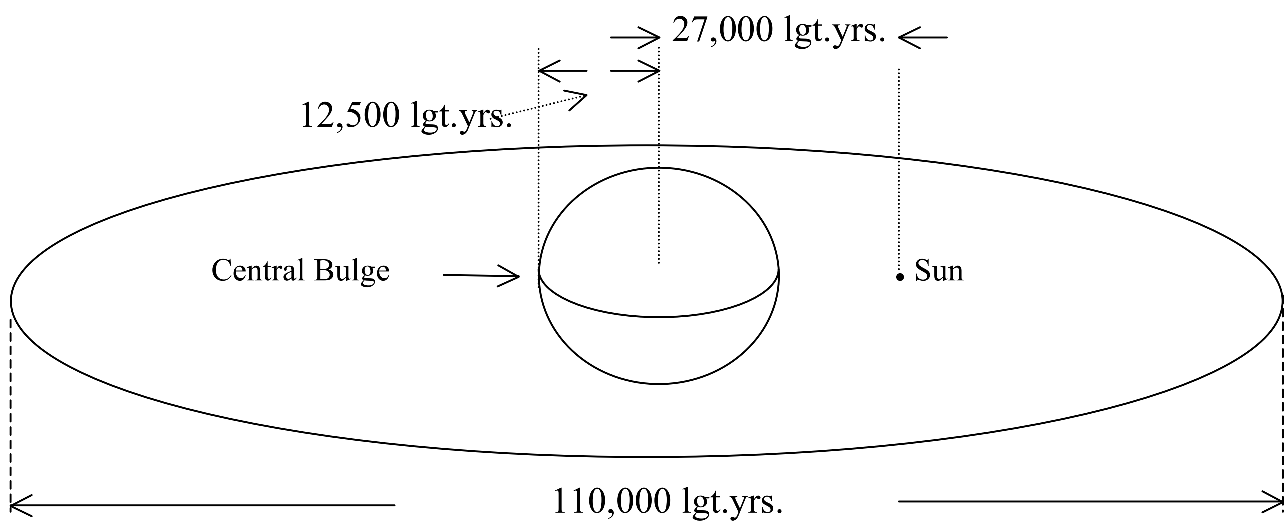

Fig. I.7: Dimensions of the Milky Way Galaxy

The Sun completes its orbit in about 235 million years! This means that the last time we were in our present position relative to the central bulge was in the early part of the Triassic period with the super continent, Pangea, at the beginning of the time of the dinosaurs! Two orbits ago life was just coming ashore from the sea, the North American continent was on a collision course with Europe and the first land plants were about to appear. If we accept current estimates of the age of the Sun at about 4 and ½ billion years, the Sun has only made about 19 orbits of the Galaxy since its formation.

Now with all these vast numbers appearing you might want to be sympathetic to the astronomers who thought the Milky Way encompassed all the matter of the Universe. In fact, before the dimensions of the Milky Way were even pinned down it had become clear that the Milky Way was just a very small part of the **Cosmos**!

7. The Local Group: Like satellites around a planet or planets around a star or stars within a galaxy, galaxies, themselves, tend to aggregate together within gravitationally bound groups. Unlike the first two kinds of groups, groups of galaxies are not usually overwhelmingly dominated by one galaxy that is enormous compared to the others in the group. And unlike stars within a galaxy, the number of galaxies within a group is, by comparison, very modest. Still, groupings of galaxies is common and our galaxy, the Milky Way, is no exception. We call the group to which the Milky Way belongs, the **Local Group** and it contains about 50 galaxies (even with the latest instruments it can be difficult to determine whether some observed objects are galaxies belonging to the group or not) (**Fig. I.8**). Our galaxy is very near the center of the Local Group and is one of the two largest galaxies in the group, the other being the **Andromeda Galaxy**, which is about as large as the Milky Way and is about 2 million lgt.yrs. away (Yes, even at a distance of 2 million lgt.yrs. these objects are gravitationally influencing one another.). The diameter of the Local Group itself is about 8 million lgt.yrs.!

Now these distances are such that what we observe today is representing things that happened a long, long time ago! We see Andromeda as it was two million years ago and anything occurring in Andromeda now will not make itself known to us for another two million years. If the SETI program received signals from intelligent life somewhere in Andromeda, it would be a signal transmitted two million years ago and the Andromedans would not receive our response for another two million years. That’s a long time to wait for an answer! This all presumes, of course, that we and the Andromedans are constrained by the physical laws we presently recognize.

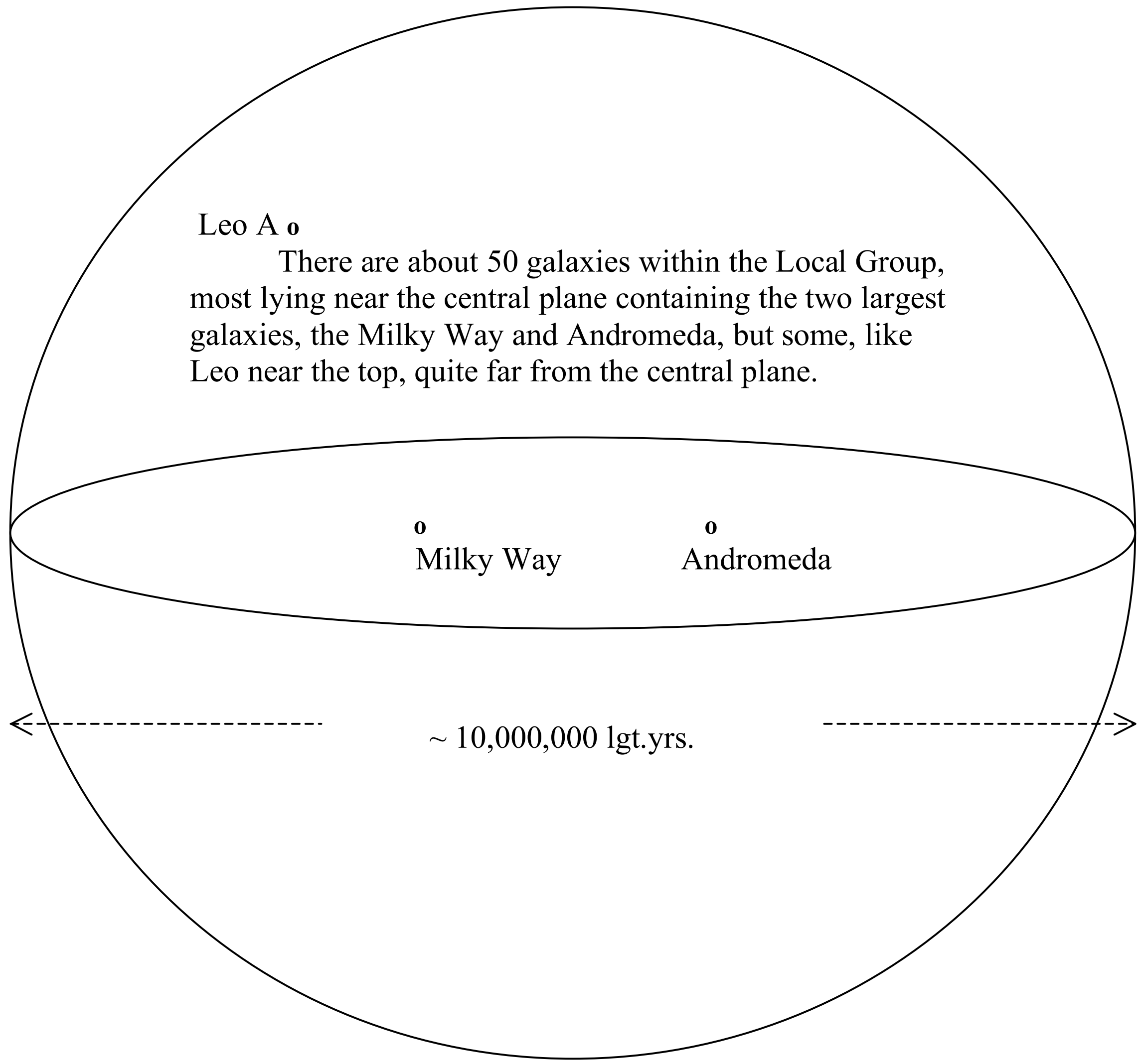

Fig. I.8: Dimensions of the Local Group

Notwithstanding the fact that the number of galaxies in the Local Group, and in all groups of galaxies thus far observed, is far smaller than the number of stars within single galaxies, it is still far more likely for galaxies to collide than for stars to collide. The reason is simply that *the sizes of stars compared to the distances between stars in a galaxy is so much smaller than the sizes of galaxies compared to the distances between galaxies in a group*. For example, the nearest star to our Sun, Alpha Cantauri, is about 30 million solar diameters distant from the Sun, while Andromeda, not the nearest galaxy to our Milky Way, is only about 20 Galactic diameters distant from the Milky Way. Collisions between stars do take place, but given the number of stars they are far less common than collisions between galaxies.

But this raises a question of what one means by a 'collision'? Galaxies, after all, are composed of stars. How can galaxies collide more frequently than stars if they're made of stars? The answer is that galaxies 'collide' by passing so near to each other, or even by passing *through* each other, that their mutual gravitational influence seriously disturbs the stellar arrangements within them. And this can happen without any star from one galaxy 'colliding' with any star from the other galaxy. The stars don't collide but their orbits or paths are greatly disturbed and they may even end up changing galaxies as a result of the galactic 'collision'. Indeed, the original galaxies may cease to exist as a result of their 'collision'.

We should also take the phrase 'frequency of collison' with a grain of salt. Galactic collisions take millions of years to occur from initial mutual disturbance to final resumption of quiescence. In our brief tenure as astronomers the human species has merely glimpsed many collisions in various stages of occurring.

8. Superclusters, Walls and Voids: We're getting near the end of the line. We could go on to examine the distances to individual galaxies outside the Local Group, or to the nearest groups of galaxies, or examine the sizes of groups of groups of galaxies – for such things, called **superclusters**, sometimes containing hundreds of galaxies, do exist in considerable number, as we came to realize in the 1980s. The distribution of superclusters is not uniform but, instead, has them concentrated in web-like walls, along with many other smaller clusters (**Fig. I.9**). Between these walls are great voids, largely empty of galaxies or ordinary matter of any kind. These walls and voids comprise structures with dimensions of hundreds of millions of light years.

Beyond these, the most distant objects or events – (we're not always sure just what they are, some of them seem to be enormous stellar explosions we call **hypernovae**) – we've ever seen (or detected without really 'seeing' them) are *about* 13 billion lgt.yrs. away. A few years ago we thought some of the objects were about 15 billion lgt.yrs. away but such distances are hard to pin down and they've recently been reassessed downward. Part of the

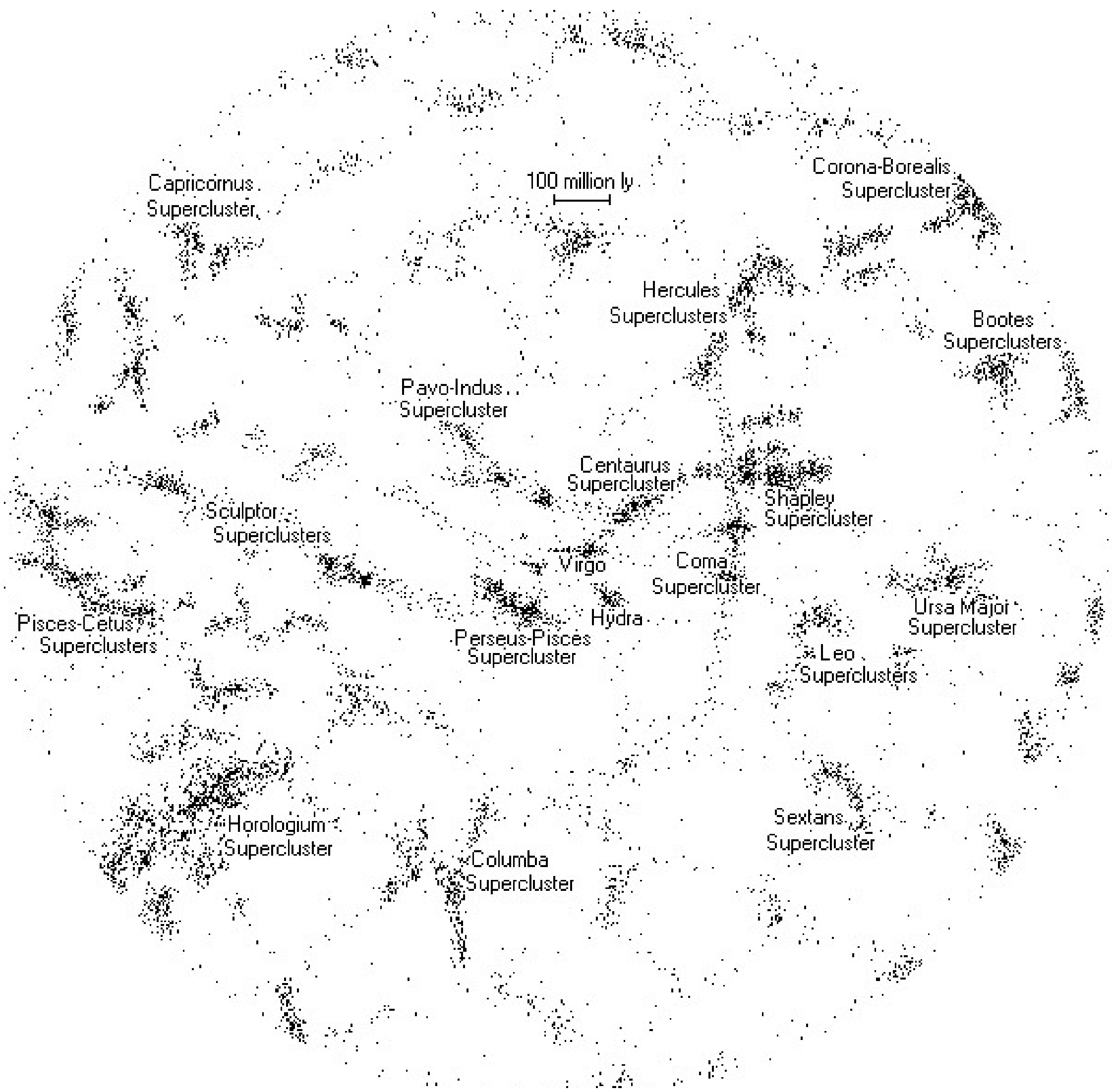

Fig. I.9: Distribution of Superclusters and the Walls they form enclosing Voids. The dimensions across the image and from top to bottom are about one billion light years.

reason is that we now think the Universe is about 13.7 billion years old and if that's correct we couldn't possibly detect anything that *was* more distant than 13.7 billion lgt.yrs. when it emitted the light we're *now* seeing. Radiation from any such object wouldn't have had time to reach us yet.

So somewhere between 13 and 14 billion lgt.yrs. is the upper limit on the distance scales we have to try to wrap our minds around *for now*. And that distance is just about 1,370 times the 10 million lgt.yr. diameter of the Local Group. So our last diagram, **Fig. I.10**, takes us to the limits of the detectable Universe.

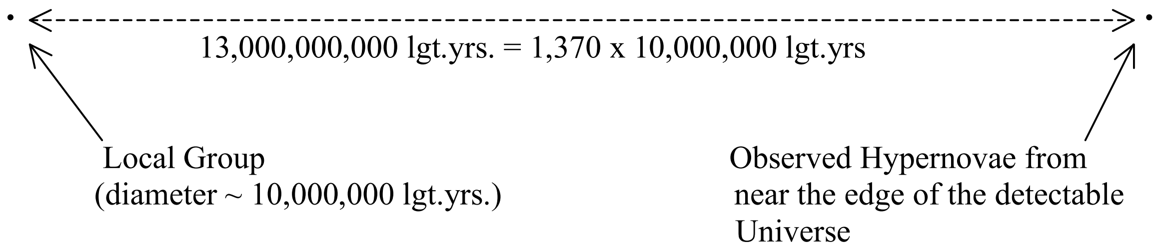

Fig. I.10: Distance to the edge of the detectable Universe

Appendix: Olber's Paradox.

If, indeed, the number of stars within large spherical volumes increased, on average, with the cube of the radius of the volume, i.e., $N \sim R^3$, then the number of stars within a spherical shell of fixed thickness would increase, on average, with the square of the radius of the shell, i.e., $n \sim R^2$. Once the spherical shells are large enough to include enough stars each, the average luminosity per star, L, would be constant, i.e., not vary from shell to shell as the shells become larger. Now, since spherically spreading light intensity diminishes as $1/R^2$, the luminosity we would receive from any one such shell must satisfy, $I \sim n L / R^2 \sim L$, i.e., the luminosity is the same from each sufficiently large shell. But if space is infinite and the stars uniformly distributed on average, as we assumed, there are an infinite number of such shells all sending us the same illumination. The night sky should be ablaze with blinding light!!

Resolution: The light from the larger shells takes longer to reach us and if the Universe is not eternal but has only existed for a finite time, we have not yet received any light from shells beyond a certain size. If this were all we might expect the night sky to grow brighter as light from the more distant shells reaches us. But as time goes on the light from the nearer shells is from older stars which will eventually die. As the more distant shells check in the nearer shells grow dim.