Clusters of Galaxies and the Expansion of the Universe

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A Basic Overview

So after going through the mathematical knowledge of *Tensors*, we head on to understanding very interesting concepts and phenomenons from the book – **The Physical Universe : *Frank H. Shu***. Though the topic we are going to see is self-explanatory in its title, it is good to break it down. We would see clusters of galaxies, be it only 2 membered(*binary*) or multi-system(*millions or billions!*). The galaxy clusters have very peculiar features, some of which could be explained, yet some remain questionable till date. Followed by this, we would try to find answers behind the expansion of the universe, the ***Hubble's Law*** and its interpretation. And **don't worry at all**, since we have tried to explain in the easiest way possible! So without any further ado, let's ride along......

1 Interacting Binary Galaxies

Galaxies were generally discussed as isolated entities, free from the influence of other galaxies. In reality though, just as there are interacting binary stars ,there are interacting binary galaxies observed as well. Strongly interacting pairs of galaxies constitute a very small percentage of the total number of galaxies known to us .Spectacular examples of rings, bridges and tails have been catalogued by *Vorontsov-Velyaminov* and by *Arp*. If two galaxies have very different masses, then the **smaller one can pull out material from the near side of the larger galaxy** into a **bridge** that temporarily spans the gulf between the two galaxies .

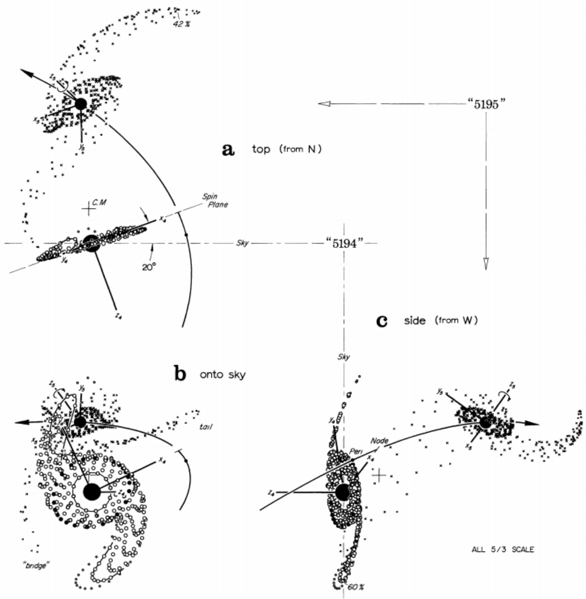

Figure 1: *The above figure shows a numerical simulation of a bridge-producing encounter . A direct close flyby of a small galaxy past a big disk galaxy draws out a bridge of material that temporarily spans the gulf.*

If the encountering galaxies have nearly equal masses , then a tail from each galaxy may develop that generally extends away from the main bodies .This non-intuitive result arises as the tidal interaction is much stronger as compared to the *familiar example of the Earth-Moon system*.

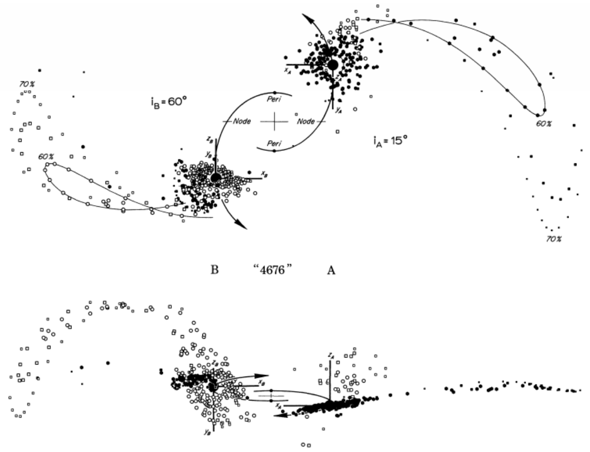

Figure 2: *The above figure shows how a direct flyby of two disk galaxies of comparable masses yield two tails that extend away from the main bodies.*

Long bridges and tails are best produced when the orbit of two galaxies are bound, so that the two systems are not flying past one another too fast when they reach the closest approach. In very rare cases, when galaxies interpenetrate, exotic looking **ring galaxies** can be formed .

2 Mergers

Close encounters between galaxies excite much internal motion in them. The energy to produce these motions must come from the orbital motion. In a gravitating points (stars) system, it disperses as radiation. The collection of stars would tend to conserve its total energy. The stars might transform orbital energy into random motions.

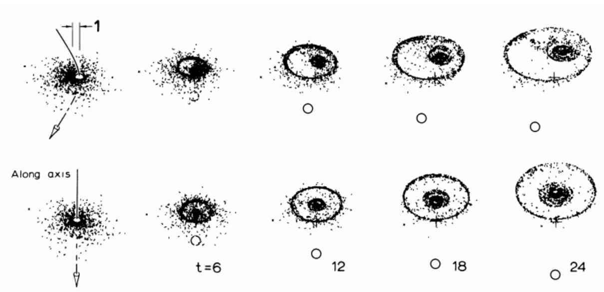

Figure 3: *Two numerical simulations of ring-producing encounters. An interpenetration of a disk galaxy by another massive body yields rippling waves of rings*

Indeed, it can be argued on statistical grounds that repeat encounters between two bound galaxies must tend to bring the two galaxies closer together, consistent with the constraints of the **conservation of total angular momentum and total energy**. This is based on the *second law of thermodynamics*: the encounters increase the entropy of the universe.

2.1 *Merger Process*

The close encounter of two bound spiral galaxies,must produce a merger into a single pole of stars. This merger process involves a form of ***violent relaxation*** in which violently changing gravitational fields help to produce a final smooth distribution of stars. Such a pile of stars would probably strongly resemble an *elliptical galaxy*.

2.2 *Alar Toomre's argument*

His argument is beguiling,and proceeds as follows. Of the 4000 or so NGC galaxies, perhaps a dozen are interacting systems exhibiting **spectacular bridges** or **tails**. On the other hand, the numerical simulations show that such geometric forms are transient phenomena that cannot be maintained for more than a few times 10^8 years.

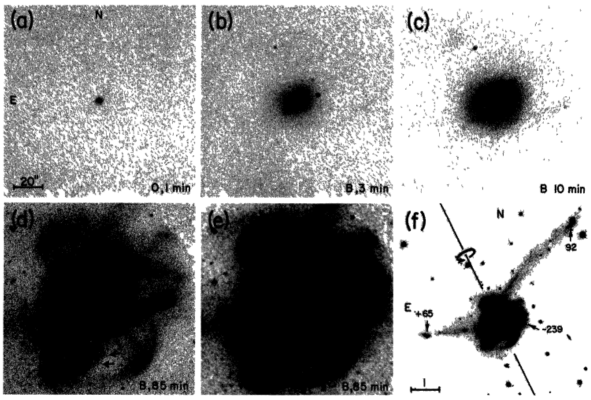

Figure 4: *Successfully deeper photographs of NGC7252 reveals complex set of filaments surrounding a central body that resembles a giant elliptical galaxy.*

Question 1

Could there be any flaws in his argument? Think and explore.

3 Hierarchical Clustering

Well, well ,well ...So previously we have seen double galaxies, but they do exist in the form of small rich clusters as well. In the Local Group (*a group of galaxies*) like the one containing our **Milky Way** and **Andromeda**, there may be dozens as well members extending over a radius of million light years. This can even exist on a further larger scale, extending to hundred of million light years, earning the name Super-cluster. These have been confirmed to exist by Holmberg, Reiz and de Vaucoulers, yet whether clusters of super-clusters exist is questionable.

3.1 *Rich Clusters of Galaxy*

The most closest rich cluster to us is the **Virgo cluster**. It boasts of a collection of 200 bright galaxies (68% spiral : 19% ellipticals : rest irregular/unclassified), and one of the brightest galaxy being Messier-87(*M-87*), an elliptical galaxy. Another notable one is *Coma cluster*, roughly 7 times as far as Virgo.

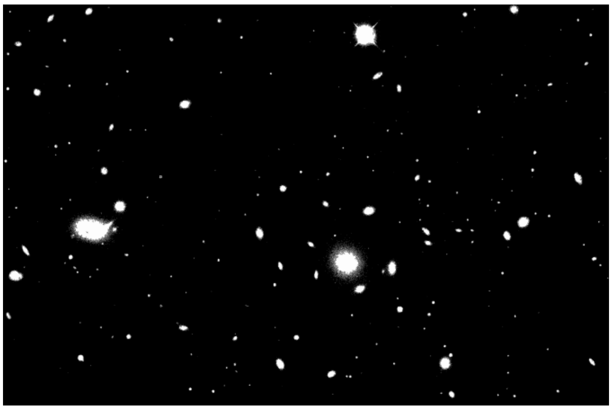

Figure 5: *Central region of Coma cluster containing two super-giant ellipticals,which have grown bloated.*

These rich clusters share some **common features** :

- **Scarcity** in the number of Spiral galaxies.
- The presence of one or two very luminous supergiant elliptical galaxies near the center of cluster. This supergiant elliptical galaxy is known as **cD galaxy**, for some historical reasons which the author finds "*not particularly illuminating*". As a result of their size, they dominate the appearance of the cluster.

To know why these common features come to the picture, let us head to the next sub-sections.

3.2 *Galactic Cannibalism*

A cD galaxy is seen to have possession of envelope of stars, like a bulge. An example is NGC6166, a radio galaxy residing in Abell cluster 2199. Oemler noted in his surface photometry on these extended envelopes of cD galaxies that the rate of dropping of brightness from the center is slower than given by **de Vaucoulers law**, which applies to ordinary galaxies.

$$\ln I(R) = \ln I_0 - kR^{1/4} \tag{1}$$

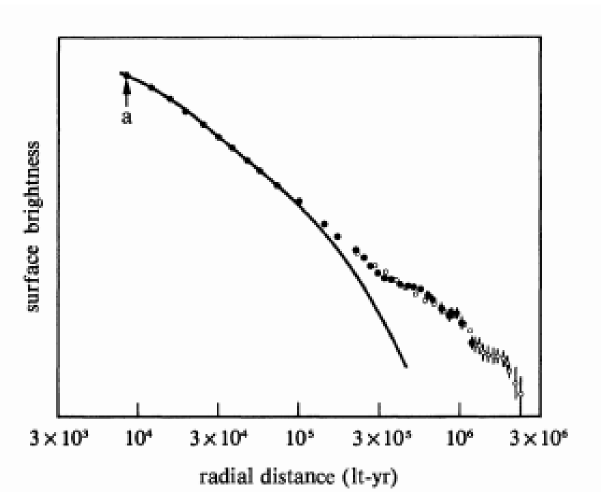

Figure 6: *Deviation of the law for cD Galaxy.*

Hence it was proposed that these cD galaxies grow bloated by cannibalising(*yes...like the old-age man cannibals*) on smaller neighbours. This is explained by two phenomenons :

- **tidal stripping**, and
- **dynamical friction**

3.2.1 *Tidal Stripping*

This concept is commonly known to us, as we hear about tides in our common life. The principle is based on ***Roche's Limit***, that is, an object of mass m and radius R, held together by self-gravitation and which approaches within distance r of massive body M, will be ripped apart by tidal forces at the critical limit of

$$r = (\frac{2M}{m})^{1/3} R \tag{2}$$

A quantitative visualisation can be that a 500 times heavier cD galaxy can rip apart a galaxy stars at r = 10R. Not all shredded material can be captured gravitationally, some of the stars may enter the orbit about cluster as a whole.

Demystifying the Equation: Consider a mass m body of radius R placed in a circular orbit of radius r with massive body M at the centre. The gravitational forces at the extreme ends of the body m would be $\frac{GMm}{(r-R)^2}$ and $\frac{GMm}{(r+R)^2}$.

The difference between the forces at ends can be calculated to be found as, under the assumption that $R \ll r$

$$\frac{GMm}{(r-R)^2} - \frac{GMm}{(r+R)^2} = \frac{2GMmRr}{r^2 - R^{2^2}} \approx \frac{2GMmR}{r^3} \tag{3}$$

Stars at extreme ends of m experience a force per unit mass of

$$\frac{Gm}{R^2} \tag{4}$$

If disruptive acceleration of $\frac{2GMR}{r^3}$ exceeds $\frac{Gm}{R^2}$, galaxy m will be ripped apart. Hence equating both the forces would given the limit r, and hence the above equation(2).

But there is **an issue**. Galaxies do not have uniform distribution, and the density is largest at center. The rarified outer portions will be exceeding Roche's Limit and tidal stripping would effectively occur. But the dense cores will have fall quite deep into the heart of cD galaxy to have some effect. Since this deep encounter is rare, a cD Galaxy has to do something else to gobble the cores of other galaxies, which it does by *Dynamical Friction*.

3.2.2 *Dynamical Friction*

Cause of its **origin** can be easily understood. As heavy dense core *m* moves through a medium of stars, the core deflects the stars on it way. These deflections kind of pile up behind *m*, and this extra mass starts pulling the mass *m*, and reduces it velocity relative to the stars. This net effect of dynamical friction ultimately brings the galactic core to center of a cD galaxy. And now......its *DINNER TIME*!

The core of the galaxy is highly massive, hence the defections are correspondingly greater. Quantitatively, the dynamic friction can bring the core of galaxy near the center of a cD Galaxy in terms short compared to 10^{10} years, the age of the universe.

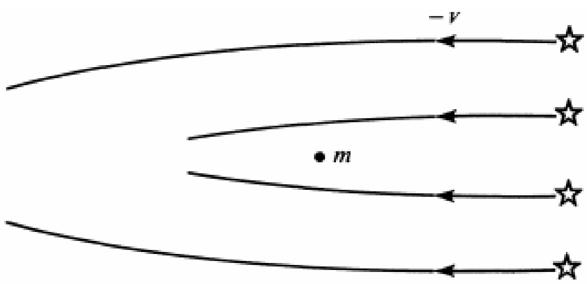

Figure 7: *Dynamical friction arises when a mass m moves at a speed wrt stars distribution which are statistically at rest.*

The Relaxation Time (t_{relax}): Just like we kiddos studied in a resistance wire, a rough estimate of the relaxation time for stellar encounters can be estimated. Considering all stars to be a sphere of radius r, if any star were to enter this sphere of influence, it could suffer an encounter. And hence t_{relax} is the **time between two successive encounters**. If star density is n, velocity of star V, then we want the cylindrical volume of star's sphere of influence swept in one t_{relax} to contain one star. That is

$$n(\pi r^2 V t_{relax}) = 1 \tag{5}$$

A *sensible choice* of r would be at which the gravitational PE of pair of stars equals a typical KE of a star.

$$\frac{Gm^2}{r} = \frac{mV^2}{2} \tag{6}$$

Thus t_{relax} comes out to be $t_{relax} = \frac{V^3}{4\pi G^2 m^2 n}$. But deep analysis shows that many smaller deflections are much efficient than one big deflection, by a factor of $\ln(\frac{2R}{r})$, R being radius of cluster-core. Hence the equation comes out to be

$$t_{relax} = \frac{V^3}{4\pi G^2 m^2 n \ln(\frac{2R}{r})} \tag{7}$$

Now **back to our case**, taking mass m of galaxy, mass of each scattered star to be m_*, N stars in volume $\frac{4\pi R^3}{3}$. Also $Nm_* = M$, mass of the cD galaxy. So the equation simplifies to:

$$t_{relax} = \frac{(rV)^3}{3G^2 Mmn \ln(\frac{rV^2}{Gm})} \tag{8}$$

Question 2

Check whether big galaxies would be cannibalized in preference to smaller ones.

3.3 *Hot Gas in Rich Clusters*

Satellite observations in early 70s showed that X-rays pour from spaces between galaxies in rich clusters. It was concluded that this occurred due to presence of *hot gases with temperatures between* 10 *and* 100 *million degrees Kelvin*. The mass of these gas was nearly **comparable** to luminous part of the clusters. The **origin** of this gas was debatable – earlier it was believed that the gas may have come in clusters from intergalactic space. But the analysis of gas showed presence of elements like iron, which is synthesised in deep core of the massive stars. Hence it is believed to come from within the galaxy.

Ideas and Hypothesis

- Mathew and Baker proposed that the interstellar medium might be so hot in the elliptical galaxies that gas lost from stars would continuously blow out of the galaxies, like *solar wind carries material away from corona of the Sun*. This would work for both isolated elliptical as well as those in the clusters. In **spiral galaxies**, there is too much gas in the disk to maintain such a high temperature, so it was hypothesised that wind mechanism is **inefficient** here for removing gas from disk systems.

- A more efficient method **ram pressure** was also proposed, which was created by relative motion of galaxies through cluster medium. *This is similar to how wind knocks off the hat of fast-pedaling cyclist.*

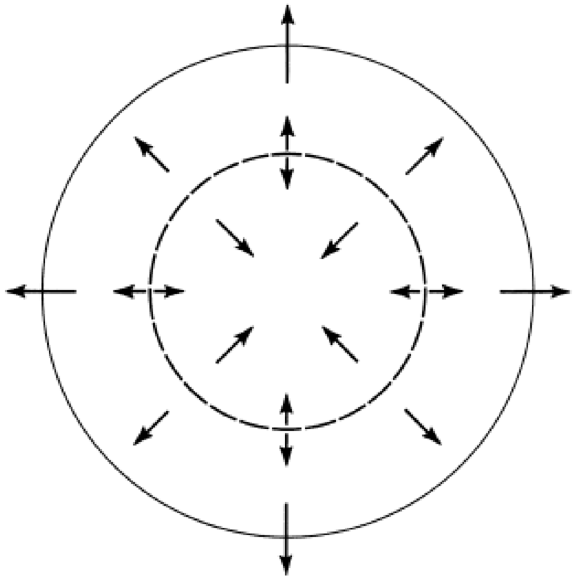

Figure 8: *Gas expelled from stars in main body of elliptical galaxy may heat up and blow outward in galactic wind, or flow inward toward galactic nucleus.*

3.4 *Missing Mass in Rich Clusters*

Shane and Wirtanen and de Vaucouleurs formulated that the number of galaxies per unit area of Coma cluster varied with distance r from center according to

$$\eta(r) = \eta(0)exp[-(\frac{r}{r_0})^{1/4}], \tag{9}$$

$\eta(0)$ and r_0 being constants.

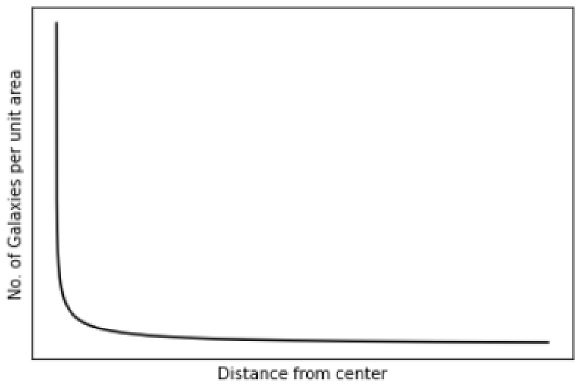

Figure 9: *Plot of the equation(9)*.(Plotted via matplotlib)

Note This law is similar to the one given by de Vaucoulers for the **luminosity per unit area** of elliptical galaxy as a function of r from its center.

$$\lambda(r) = \lambda(0)exp[-(\frac{r}{r_0})^{1/4}], \tag{10}$$

Astronomers like Zwicky and Smith soon realised that the total mass needed to bind the cluster by self-gravitation exceeded that present in optically luminous matter by roughly a factor of 10. From the previous section we know that the mass in the hot gas is almost equal to the luminous part, but still we are off by a factor of 5. Some proposals to counter this discrepancy are :

- **Low-mass stars**, tied to the halo of optical galaxies or loosely spread throughout the cluster.
- There exists in the cluster 10 times more stars as captured in our **current image photographs**.
- **Gas** that escapes from a galaxy would be retained by cluster owing to its large binding mass.

3.5 *Unsolved Problems Concerning Groups and Clusters*

Although most astronomers agree that the missing mass isn't really missing, and that it's just in a non-observable form – a minority of them, voiced by V.A. Ambartsumian and H.C. Arp, believe that our general of view of clusters being only gravitationally bound is wrong, and some of them maybe young systems in which individual galaxies are expelled from the cluster.

This view is counter-argued via following arguments:

- The smooth appearance of the spatial distribution of member galaxies only suggest that these systems are in **quasi-mechanical equilibrium**.
- If they weren't gravitationally bound, the **time to disperse** would be of order 10^9 years, the time to cross cluster diameter. As the age of universe is of order 10^10 years, why most of the clusters can be found in groups at present cannot be understood.
- This radical proposal would overthrow most of the established knowledge. But it is **not backed by** very convincing arguments to be accepted by other astronomers.

4 The Expansion of the Universe

Our universe is continuously expanding and this can be understood by the red-shift of the galaxies. First, we will understand the red-shift and the blue-shift: ***Red-shift and Blue-shift*** describe how light shifts toward shorter or longer wavelengths as galaxies moves. When an object moves away from us, the light is shifted to the red end of the spectrum, as its wavelengths get longer.

4.1 *The Extra-galactic Distance Scale*

Astronomers use different operations to measure the distances. They are given in the box:

Local distance indicators:
  Classical Cepheids (standard candle)
  Novae (standard candle)
  RR Lyrae variables (standard candle)
  W Virginis stars (standard candle)
Intermediate distance indicators:
  Brightest nonvariable stars of a galaxy (standard candle)
  Brightness of globular clusters (standard candle)
  Diameters of giant HII complexes (standard ruler)
Global distance indicators:
  Fischer-Tully relation (standard candle)
  Brightness of Sc I galaxies (standard candle)
  Supernovae (standard candle and indirect ruler)
  Three brightest galaxies of a cluster (standard candle)
  Diameters of bright galaxies (standard ruler)
  Baldwin relation for QSOs (standard candle)

Figure 10: *Extra-galactic Distance Indicators.*

All the methods for measuring the extra-galactic distances reduce to either the

- method of the **Standard Rulers**, or
- the method of **Standard Candles**

4.1.1 *Method of Standard Rulers*

The object of known luminosity and known distance will have a certain fraction of its light intercepted by the telescope. An object of the same luminosity at a greater but unknown distance will have a small fraction of the light intercepted by the telescope. *The ratio of the distance is inverse square root of the ratio of apparent brightness*.

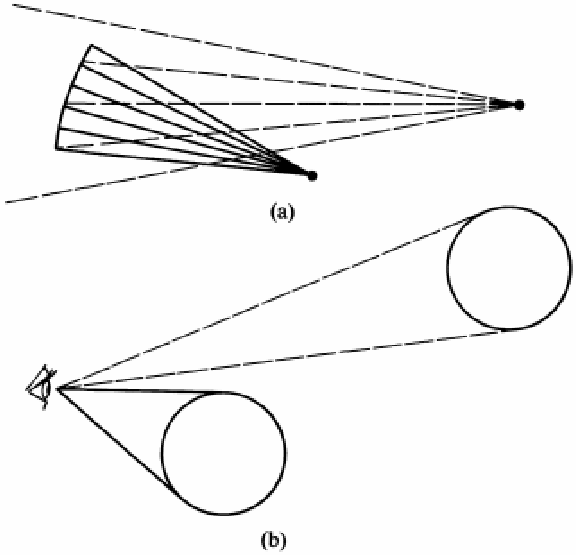

Figure 11: (a) *Method of standard candles*, and (b) *Method of standard rulers*.

4.1.2 *Method of Standard Candles*

An object of known linear size and known distance will subtend a certain angle. An object of the same linear size at a greater but unknown distance will subtend a smaller angle. *The ratio of the distances is inverse of the ratio of subtended angles*.

4.2 *Hubble's Law*

Hubble was the first to give the correct law of the expansion of the universe. He stated that the further away a galaxy is, the faster it tends to recede from us.

$$v = H_0 r, \tag{11}$$

where H_0 is the Hubble's constant, v is the velocity and r is the distance.

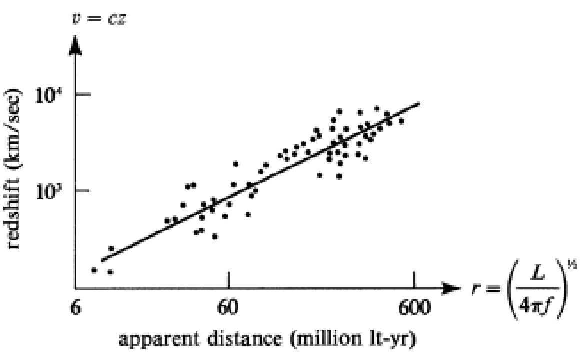

Figure 12: *Hubble diagram for Sc I galaxies. Data points well-fit around straight line, demonstrating* $v \propto r$

So, the value of H' = 15 $kmsec^{-1}/(millionlightyear)$. This value was initially obtained but on many more experimentation, an anomaly was found by Aaronson and coworkers that the **value of the Hubble's constant is different in each direction of the space**. Now an arbitrary value of the Hubble's constant is accepted as: H' = 20 $kmsec^{-1}/(millionlightyear)$.

4.3 *Naive Physical Interpretation of Hubble's Law*

Imagine that the explosion (*big bang*) occurred at the time $t = 0$, and since then time elapsed = t sec, and we are at the center of the explosion. The freely moving galaxy has travelled a distance of $v = r * t$. So, on rearranging, we have: $v = \frac{r}{t}$. Comparing it with Hubble's law, we have $H' = \frac{1}{t}$. So, now H'^{-1} is called as the Hubble's Time. Now, basically ignoring gravity, we will get the *exact age of the universe* = $1.5 * 10^{10}$ years. Though it later changed a bit but the formula is accurate up-to the order of magnitude. So, the universe is roughly 15 billion years old. . . **ASTONISHING!!!!!**

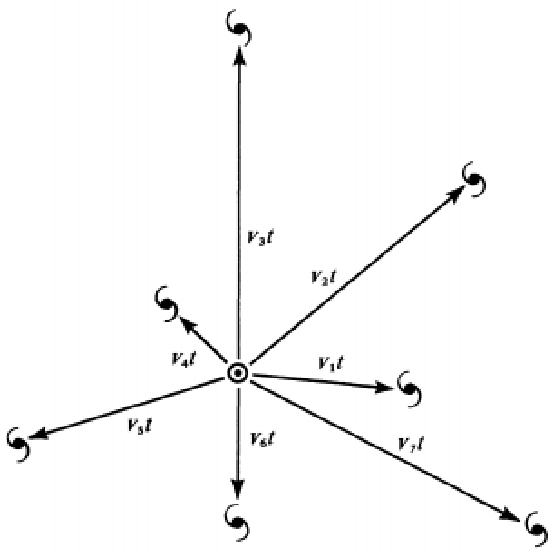

Figure 13: *Visualisation of the physical interpretation of Hubble's Law*

On the Ending Note

So we realised that even on such huge scales of galaxy clusters, it is the gravity which is dominating and playing all the game. The tendency to accumulate more and more in the centre due to self-gravitation, tidal stripping, friction due to relative motion, everywhere gravity explains the interesting phenomenon. But the universe is expanding, so does gravitation has no say at the cosmological scale?? Well, not quite.

> "
> *Gravitation is the very fabric of structure of space and time.*
> "

So, with these thoughts in mind, head on to the next topic exploring the answers – ***Gravitation and Cosmology***.