1ST RESEARCH PAPER

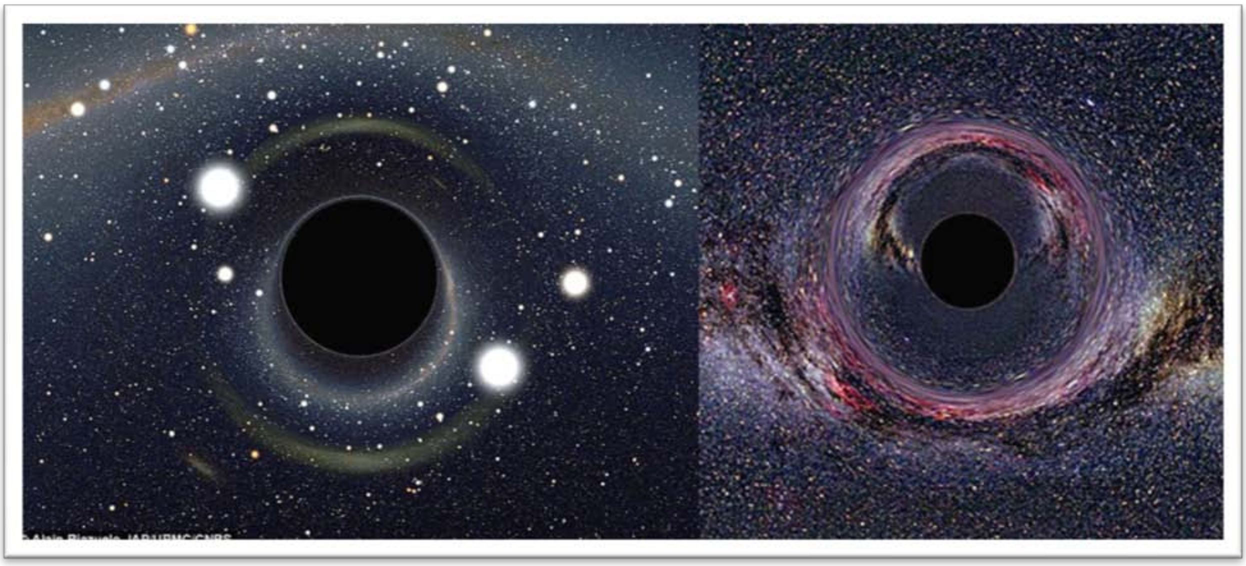
HAVE you ever heard of black hole mergers? How, where and why do black holes merge and what effects do these mergers have on us, here on earth? Astrophysicists see a lot of possibilities of black hole mergers in the universe. The only means of "seeing" black hole mergers is through a 'gravitational wave' eye.
Black holes radiate too little electromagnetic radiation of their own to be seen through electromagnetic wave detectors. But when two black holes merge, they radiate lots of gravitational waves. These gravitational waves can be detected once the sensitive gravitational wave detectors that are being built at various places in the world become functional. So far, observation of gravitational wave emission by compact stars has been indirect, Direct detection of gravitational waves will be a big breakthrough, as this will open a new window to the universe. Besides giving one more direct test of Einstein's general relativity, gravitational wave detection will lead to observations of many frontier astrophysical phenomena.

Black Hole Mergers: Where and How?

Generally we picture a black hole as an absolutely dark, calm and motionless object, sitting aloof at a point in space. Or an absolutely dark and calm object going round the centre of its parent galaxy. Or, at best, a companion in a double star revolving in a circular orbit, accreting matter from the companion star and thereby causing the falling matter to emit X-rays. (Such X-ray sources in the sky in fact make the best candidates for 'stellar' black holes,) Now, why do two black holes come closer and merge?

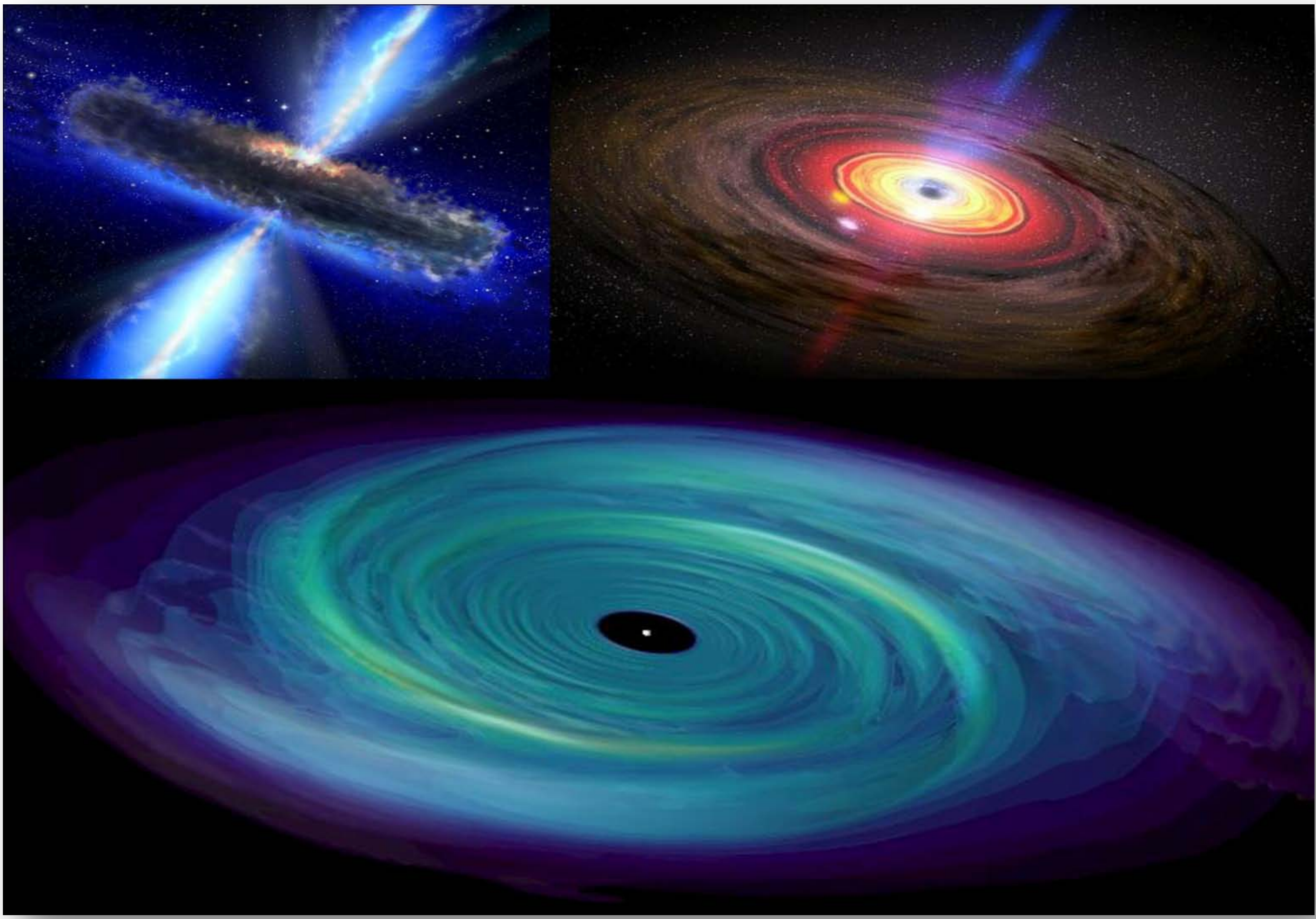
More than half of the stars in a galaxy are double stars (two stars revolving round their common centre of mass). 'Double stars are rather the 'rule' than exception', goes the saying! And there is every possibility that both the stars in a binary (another name for a double star) would become black holes! According to classical electrodynamics, accelerated electric charges radiate electromagnetic waves and thereby lose energy. Similarly, accelerated gravitating bodies radiate gravitational waves and lose energy. This is an important consequence of general relativity.

The stars in a binary, being in accelerated motion, radiate gravitational waves and thereby lose energy (remember that every *curved* path motion is an accelerated motion, thus, uniform circular motion is also an accelerated motion). The loss of energy causes the decrease in the separation of the companions. The bigger the acceleration, the bigger is the rate of radiation and the rate of decrease of their separation.



Every binary, thus, in principle, radiates gravitational waves but not appreciably. By the time the stars in a binary reach the stage of becoming white dwarfs, neutron stars or black holes, they come closer, their accelerations are now bigger and radiation of gravitational waves from them becomes appreciable. Russell Hulse and Joseph Taylor Jr. could detect the loss in energy of a binary pulsar (rotating neutron stars) by radio observations over a period of nine years and found it to be decreasing at the rate predicted by general relativity. This earned them the Nobel Prize in Physics in the year 1993.

The radiation of gravitational waves by a binary ultimately causes the merger of the two stars it constitutes. Astrophysicists did see this possibility, but did not know until recently the details of how this phenomenon would occur: As two black holes merge, how much energy is radiated as gravitational waves? What is the shape of the gravitational waves radiated? Only lately there has been some success in getting answers to these questions.



Black Hole Coalescence

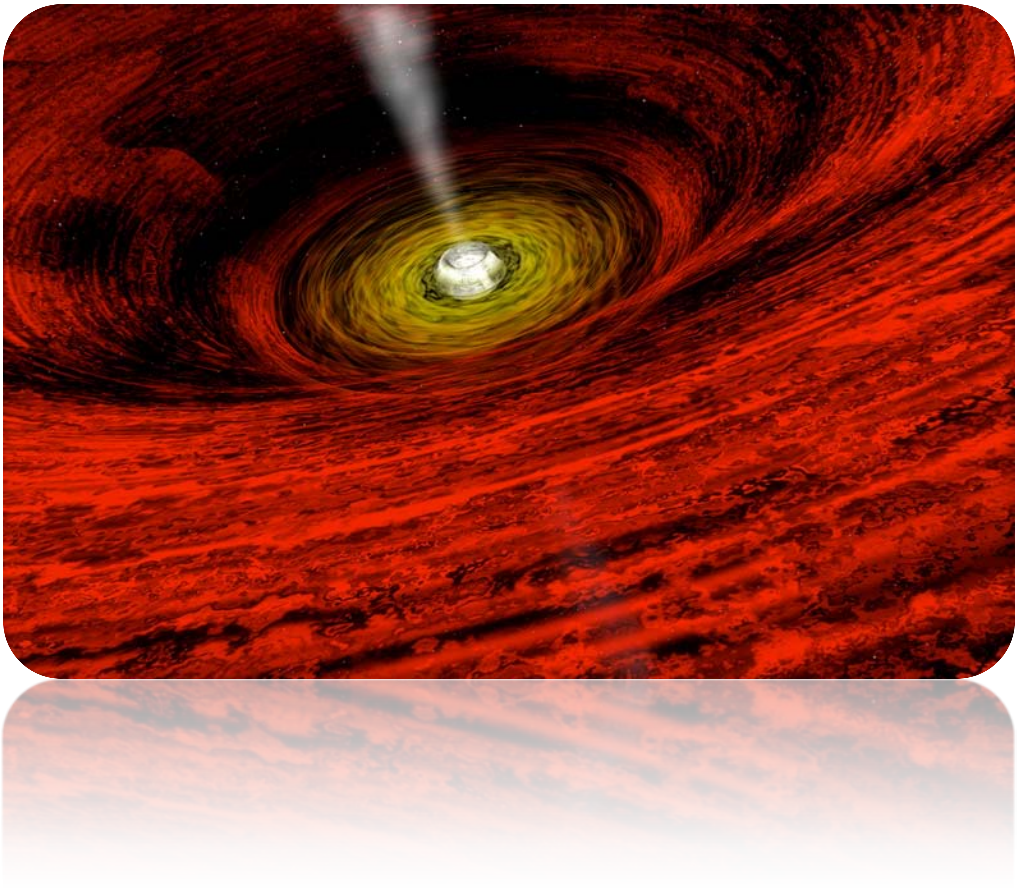
Theoretical study of black hole mergers is of utmost importance because many gravitational wave detectors are on the verge of completion. Merging black holes are not the strongest source of gravitational waves, Moreover, one must know the shape and energy of the wave,

Problems that are not amenable to analytical solutions, i.e. solutions in terms of variables, are solved numerically. Suppose for a problem with variable inputs x_1, x_2......, x_n it is not possible to get the outputs y_1, y_2......, y_m through analytical methods. The next strategy is to take particular fixed values for the inputs x's and obtain the corresponding values for the outputs y's using various approximation methods and equations of the problem. This branch of mathematics is known as numerical analysis. In many branches of natural and social sciences, phenomena are studied using numerical analysis only, for most problems do not yield analytical solutions. As general relativity is a mathematically complex theory, many problems related to gravity are studied using numerical simulation.

The phenomenon of black hole mergers is so complicated and elaborate that, for a long time, it was not yielding even to numerical analysis! The first success came in 2005 to three groups of researchers working independently at the same time. The three solutions obtained were matching, which gave confidence to these groups about the accuracy of the solution. This success triggered a lot of activity. Various groups started studying mergers of various pairs of compact objects: comparable mass black hole pairs, mass combination black holes pairs, neutron star-neutron star pairs, neutron star-black hole pairs etc.

One of the first successes was in 2005. Joan Centrella, member of one of the three successful groups from the Gravitational Astrophysics Laboratory of Goddard Space Flight Centre of NASA says: "This unleashed a gold rush, as researchers in the USA and Europe implemented the new methods and carried out a wide range of astrophysical merger simulations." Two well known researchers in the field, Thomas W, Baumgarte and Stuart L. Shapiro have said: "That computational triumph has come none too soon - physicists are on the verge of detecting gravitational waves for the first time, and at the long last they know what to look for."

Of the difficulty of the black hole merger problem and its ultimate solution, a paper by Joan Centrella *et al* says: "Over the course of more than four decades, the numerical relativity community doggedly pursued this goal, even as the problem began to seem impossible to some researchers. Overall, their success depended on a combination of algorithmic dexterity, analytical insight, numerical experience, tenacity and team work - all coupled with growing increases in computational power."



Stages in Black Hole Merger

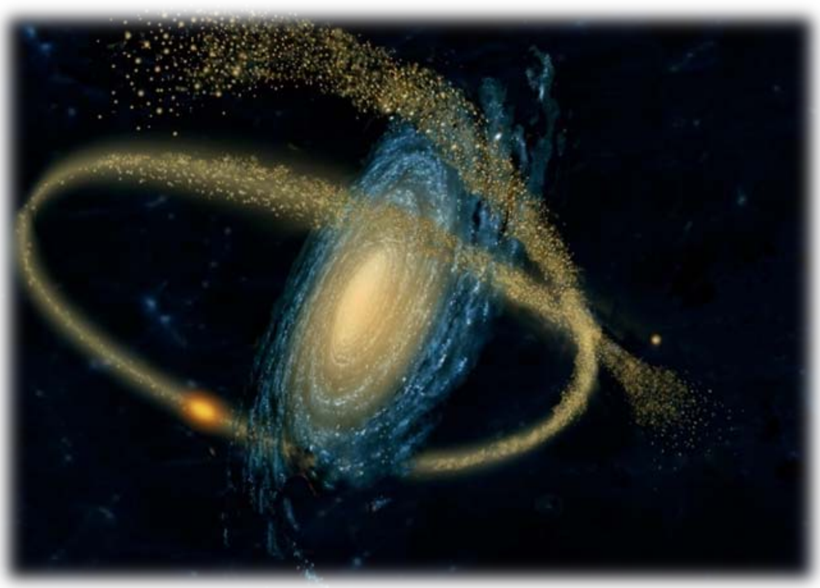
The final merger of two black holes can be divided into three stages: (i) inspiral, (ii) merger and (iii) ringdown.

I. ***Inspiral stage:*** In this stage, the holes are relatively far apart and can be considered as point masses. As these go on radiating gravitational waves, their orbits go on contracting and, in accordance with Kepler's third law of planetary motion (T2 a R3), the frequency of the gravitational waves emitted goes on increasing, Their paths are not circulars but spiral in shape as their separation is decreasing, The inspiral stage is a relatively long-lived one and continues for millions of years. However, the gravitational waves emitted by them are so feeble that these will be detected by our detectors only during the last year of this stage.

II. ***Merger stage:*** When the two holes come very close and only a few final orbits are left, the holes leave their orbits and plunge together in a rapidly shrinking spiral. The event horizons of the two merge to form a single highly distorted black hole,

III. ***Ringdown stage:*** The distorted single black hole that has resulted from the merger radiates away all its distortions in the form of gravitational waves and becomes a smooth, symmetrical, rotating black hole. The process is similar to what happens when a bell is struck by a hammer: the bell radiates all its distortions as sound waves and rings down and so the name 'ringdown'!

The merger and the ringdown stages are very brief and last for only about 10 minutes for black holes of total mass 10^6 solar masses! But the energy radiated in the form of gravitational waves is colossus. Calculations indicate that energy radiated by these is more than the total energy radiated by all the stars of the observable universe in that time!



Ejection of Black Holes from Galaxies

In any case of a binary, the total linear momentum of the binary is zero in the centre of mass (CM) frame of the binary. Suppose two black holes of equal mass are revolving round each other. These two black holes will radiate gravitational waves equally in opposite directions. So, the total linear momentum carried by these gravitational waves will be zero (two equal and opposite vectors give o zero result). The law of conservation of linear momentum then implies that the final single black hole that will be formed due to the merger will also have zero momentum in the CM-frame as earlier. This means that the new black hole formed will move in the parent galaxy on the same path as the centre of mass of the original binary.

But if the masses are unequal, they will radiate unequally, and the net momentum of the gravitational radiation emitted will not be zero, So to conserve momentum, the newly formed black hole will acquire an equal and opposite momentum and recoil!

But what will be the total momentum emitted during a merger and what will be the corresponding recoil speed of the merged black holes was not known before. The successful simulation of black hole mergers has given the answer to this question. It has been found that the velocity acquired by the newly formed black hole due to recoil will be much bigger than the escape velocity of the parent galaxy. Thus these will be ejected out from the parent galaxy!

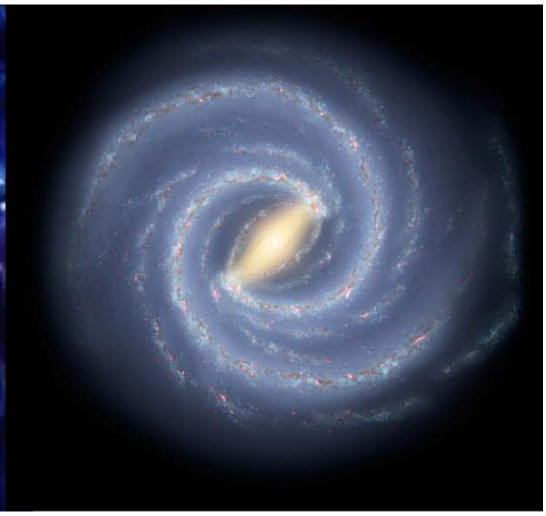
Types of Galaxies

Galaxies are classified primarily by their shape and come in 3 main types:

Elliptical*-These* galaxies have little to no structure, rotation, or interstellar matter. This results in minimal star formation and a dominance of the long lived, red stars. These ellipsoid-shaped collections of stars are the most common type of galaxy.

Spirals - These galaxies are disk-shaped with either a round central hub (unbarred) or a hub shaped like a bar (barred). They rotate with spiral arms that contain interstellar dust and gas, promoting star formation and an abundance of young stars.

Irregular- These galaxies have an irregular shape and are considered to be the result of the collisions of galaxies. As a result, they generally contain of a complex mix of interstellar gas and dust, young stars, and old stars.



Types of Black Holes

Astrophysicists distinguish between mainly the following three types of black holes: (i) Stellar black holes which have masses about 3 to 30 solar masses and which are formed due to exhaustion of thermonuclear fuel in them and the subsequent supernova explosion; (ii) Intermediate mass black holes which have masses 10^2-10^3solar masses and which form from merger of smaller black holes in the centres of dense stellar clusters or from the death of very massive stars early in the history of the universe, and (iii) massive black holes of mass 10^4-10''' solar masses which are found in the centres of most galaxies. Our Milky Way also has such a black hole at its centre whose mass has been estimated to be $4x l0^6$ solar masses.

At present, astrophysicists see the possibilities of mergers of pairs of black holes of each type. A pair of stellar black holes will merge if they make a binary. There remains a good possibility of binary formation in both stellar and intermediate mass black holes due to the dynamical processes that take place in dense stellar clusters. Similarly, massive black hole binaries form when two galaxies having black holes at their centres merge. Theories dealing with origin and evolution of galaxies imply that most galaxies merge at least once during the history of the universe. And every black hole binary has ultimately to merge!