Spin dynamics in general relativity

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Summary

Mankind always had a clue that nature can be understood and described with a limited number of concepts. Modern science explains nature in a more quantitative way: Biology taught us that the cell is the fundamental unit of life; in Chemistry molecules or atoms are the basic building blocks of materials; for Physicists, space and time are the only fundamental entities and everything else in the Universe must be understood from it.

Space, Time and Gravity

For centuries, space and time are considered as two separate things. Space was where events took place and time was a measure of change. Eventually, Einstein with his general theory of relativity revolutionised the way we think about the Universe. His elegant equations state that space and time are intimately connected and melt into one another to form space-time. Thus, the presence of large amounts of mass or energy distorts space-time – in essence causing the space-time fabric to "warp" and we observe this as gravity. For instance, the planets are moving in straight lines in the curvature produced by the sun and it appears as if they are in circular or elliptical motion around the sun. This is the central idea of General Relativity.

General Relativity is the most successful theory of gravity, describing accurately all the gravitational phenomena we know. In addition, it predicts new strong gravitational phenomena like black holes, neutron stars, compact binaries – composed of black holes and/or neutron stars, gravitational waves, and the Big Bang.

Extreme Mass Ratio System

In this thesis, I have presented the scientific work done along with my collaborators on the theoretical modelling and understanding of compact binaries. Specifically, when one of the objects in the binary system is very very small compared to the other, i.e., an Extreme Mass Ratio System. Extreme Mass Ratio Systems consist of a huge central black hole of mass million times heavier than the sun and a smaller companion with a mass of a few times that of the sun . The smaller companion can be a white dwarf, black hole or a neutron star and the central object is called a supermassive black hole.

Usually these kinds of systems are found in the centre of the galaxies. Almost all the bright galaxies accommodate one or more supermassive black holes in their centres. For example, our own galaxy Milky Way has a supermassive black hole four million times heavier than the sun, named as *Sagittarius A** and there are 28 stars orbiting it closely. Therefore by following the companions of the supermassive black holes and modelling Extreme Mass Ratio Systems will eventually help us to understand the geometry of the supermassive black hole and hence the galactic dynamics.

Black holes are objects in which a huge amount of mass is compressed into a very small volume. As a result, the space-time around them is extremely curved, such that even light can't escape once it enters into the event horizon (the point of no return) and even the tick rate of the clock reduces due to the gravitational pull. Black holes are described with three properties: mass, spin (rotation), and charge.

Technically black holes are solutions of Einstein's field equation - the master equation in the general theory of relativity. The black hole which has only mass and is spherically symmetric is known as Schwarzschild black hole. A massive compact object can also possess angular momentum, that is, rotation about its own axis. Then it is described with the Kerr metric and called a Kerr black hole. If these two kinds of black holes have charge as an additional property, then they are known as Reissner-Nordstrøm black holes and Kerr-Newman black holes. These are the four known, exact, black hole solutions to the Einstein's field equations in General Relativity.

Dynamics of an Extreme Mass Ratio System

The analytical description of systems like *Sagittarius A** is extremely complicated, as the central object is also spinning about its own axis, and many companions orbiting it. Therefore researchers have attempted to understand them in steps: describing the dynamics of a single companion around the supermassive black hole known as Extreme Mass Ratio System. Traditionally the description of spin in Extreme Mass Ratio Systems has been based on the Mathisson-Papapetrou formalism.

Mathisson and Papapetrou described the dynamics of spinning compact objects in curved space-time. But the complication in the formalism is that one has to keep track of the internal structure of the orbiting companion. Further, a fully relativistic calculation has never been done. Usually one does something called Post-Newtonian scheme in which it is assumed that the gravitational field far away from the central black hole is weak, hence Newton's Law of gravitation is used and the effects of space-time curvature are then added subsequently.

Therefore, my collaborators and I proposed an alternate complementary description for the subject. Since the mass ratio is extreme we have neglected the internal structure of the smaller companion and treated it as a point object. Thus we have generalised the Einstein's description of spinless bodies. Also near black holes the gravitational field curvature, is strong. So, we have developed completely relativistic orbits for spinning bodies by generalising the well known geodesic deviation method in General Relativity.

We then applied our new formalism to *a stellar mass spinning compact object in the curvature of a non-rotating supermassive black hole (Schwarzschild).* We analytically established three kinds of possible orbits in the relativistic limit:

Circular orbits and Innermost Stable Circular Orbits

When a stellar object is captured by the gravity of the supermassive black hole, then the body may undergo circular orbits in a fixed plane; as shown in the Fig. 6.1. This has been demonstrated with an analytic equation in our theory and the radius of the circular orbits depends on the parameters of the system: the masses of the objects and the spin of the smaller object.

The spin and orbital motion of the body are quantified by the vector quantities called spin angular momentum and orbital angular momentum. The sum of these two are denoted by **J**, the total angular momentum (shown with arrows). *For a stellar object in the planar orbit, the direction of these quantities must remain fixed as implied by our theorem.*

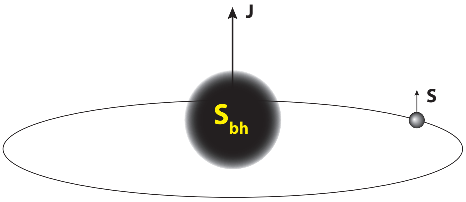

Figure 6.1. A stellar mass spinning black hole or a neutron star is orbiting a supermassive black hole in circular orbits.

The smallest circular orbit in which the stellar companion is stably orbiting the massive object is called *Innermost Stable Circular Orbit (ISCO)*. For a stellar companion which is not spinning, the ISCO is found at three times the Schwarzschild radius (the radius of the event horizon surrounding a non-rotating black hole) and it is a standard result in General Relativity. Because our orbiting object is spinning, the spin influences the ISCO. We found that, *when the magnitude of the spin increases, the radius of the ISCO increases or decreases, depending on the orientation*. Therefore, for a spinning object the ISCO can be found at more or less than three times the Schwarzschild radius.

Plane non-circular orbits and periastron shift

The orbiting body does not moves on well defined orbits like circular ones. In case the orbit is a little bit perturbed, it is still possible to have orbits in the plane. But, because of the non-constant spin the body possesses two periods. Hence the point of closest approach (periastron) and the point of farthest approach (apastron) behave in a complicated way, as the body reaches different minimum and maximum at non-constant intervals (Fig. 6.2). In addition, after each orbit the body ends ahead of the starting point. This shift in the angle of the orbit due to the warped space-time is known as *periastron shift*.

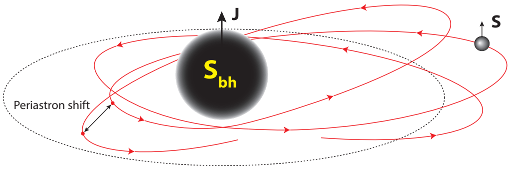

Figure 6.2. The perturbed orbit possesses a periastron shift in the plane. The spinning body reaches different periastra or apastra at non-constant intervals.

This is a well known effect in General Relativity as described by Einstein for the perihelion shift of Mercury. But *the irregular behaviour of the body with two periods is something very new which emerged out of our theory*!

Geodetic precession/de Sitter precession

For a perturbed precessing spinning object the spin precession must be compensated by the orbital angular momentum. Hence the total angular momentum **J** remains constant. Then the body goes in a periodic motion above and below the plane orbiting the massive object. In other words, the whole orbit precesses about its plane. Therefore the orbital angular momentum **L** sweeps out a cone. This effect is called *Geodetic precession or de Sitter precession* named after Willem de Sitter.

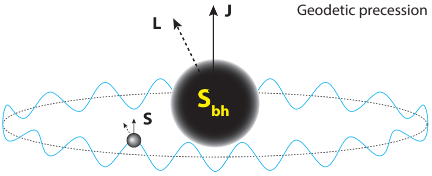

Figure 6.3. The spin precession must be compensated by the precession of the orbital angular momentum **L**. Therefore **L** sweeps out a cone.

The geodetic effect was first predicted by de Sitter in 1916, and he has provided relativistic corrections to the motion of the Earth-Moon system. Later on this effect has been found in many other systems. Here we have discovered this effect in our Extreme Mass Ratio Binaries.

Conclusion

We have described the dynamics of spinning compact objects in a completely new frame work and established three kinds of orbits and its properties. But the orbiting body can behave in more complicated ways, which is left for further investigation. For instance, when the body is orbiting at relativistic speeds it emits gravitational radiation: waves representing ripples in the fabric of space-time.

The European space agency is already working to set up a gravitational laboratory – eLISA, that will orbit the sun along with earth whilst detecting the ripples in space-time and send us the information. A study of this information can unveil the geometry around the central black hole and the stellar object populations, mass spectrum and spin. Almost all bright galaxies hosts one or more massive central black holes. When galaxies coalesce these supermassive black holes will merge eventually, releasing huge amount of gravitational radiation during the process. Thus detecting these signals will not only test theories of gravity and black holes, but also reveal information about the evolution and merger history of galaxies.

Interestingly, Einstein who discovered the gravitational waves in his theory of relativity, didn't think that its detection will ever be possible. But we can now be proud enough to live in an era, where his doubt has been proved wrong with the latest discovery of gravitational waves at LIGO observatories – the event named GW150914.