Lecture 24 : Binary Neutron Stars

In 1974, a binary neutron star system was discovered - two neutron stars going around a common centre of mass. This raised the following question: "How did such a system form?" The first part of this lecture is devoted to the evolution of massive stars in 'binary systems', and the eventual formation of a bound pair of neutron stars.

The separation of the two neutron stars was a mere million cloture's, roughly the radius of the Sun. With two massive objects in such a tight binary, General Relativistic effects were expected to be large in comparison to the GR effects, say, on the orbit of Mercury. Indeed they were! The second part of this lecture will describe the various relativistic effects that were verified to unprecedented accuracy using this system. Observations of this system also provided the very first evidence for Gravitational Radiation. Not surprisingly, the Nobel Prize was awarded to Hulse and Taylor, who discovered this pulsar, and demonstrated the existence of gravitational radiation.

The 305-meter Radio Telescope at the Arecibo Observatory, located in Puerto Rico, used to be the largest single-dish radio telescope in the world (no longer operational). It is with this telescope that Russel Hulse and Joseph Taylor discovered the now famous Hulse-Taylor pulsar in 1974 for which they were awarded the Nobel prize in 1993.

Text Books & Resource Material :

1. I. Percival, D. Richards, 1982, ***Introduction to Dynamics***, Cambridge University Press
2. D. Bhattacharya, E. P. J. van den Heuvel, 1991, Phys. Rep., 203, 1
3. J. Frank, A. King, D. Raine, 2002, ***Accretion Power in Astrophysics***, Cambridge University Press
4. T. M. Tauris, E. P. J. van den Heuvel, 2006, ***Formation and evolution of compact stellar X-ray sources***, in 'Compact stellar X-ray sources : Cambridge Astrophysics Series, No. 39', (W. Lewin, M. van der Klis, eds), 623

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Suggested Problems

1. **Visual Binary Stars**

   i. A certain optical telescope can resolve stars that are $1''$ apart in the sky-plane. Consider a binary with this minimum separation that is at a distance of 10 pc from us. Estimate the orbital period of this system, assuming the combined mass of the system to be $1M_\odot$.

   ii. How long may one require to observe this binary in order to notice that they are orbiting one another? Discuss. Justify your answer. [A sketch could be helpful.]

2. **Binary Stars : Equipotentials**

   i. Write a numerical program to draw the equipotentials of a gravitationally bound system comprising of two stars of mass $10M_\odot$and $25M_\odot$at an initial distance of 10^6km. Show all the Lagrange points and discuss the significance of all them. Identify the Roche Lobes.

   ii. Draw the equipotentials for the above system - a) after the end of the first phase of mass transfer (Roche overflow), b) after the formation of the first neutron star, c) during the second phase of mass transfer (Roche overflow). Discuss the evolution of the system considering the evolution of the equipotentials. Does the distance between the stars remain unchanged through the many phases of evolution? If not, that should also be taken into account while discussing the evolution of the equipotentials.

3. **Binary Stars : Evolution**

   i. Prove that when a more massive star transfers mass to its less massive companion in a binary system, the orbit shrinks. Also prove the reverse, that is, when a less massive star transfers mass to its more massive companion the orbit expands.

   ii. In a binary system, comprising of two stars of mass M_1 and M_2, one of the stars undergo a supernova explosion (SNE) to form a neutron star. Assume the SNE to be instantaneous and spherically symmetric. Prove that the binary would be disrupted if δM, the mass ejected from the system during the explosion, is greater than half of the total mass ($M = M_1 + M_2$) of the system before explosion.

   iii. The evolution of the semi-major axis (a) of a relativistic binary is given by the following equation -

   $$\frac{da}{dt} = -\frac{64}{5}\frac{G^5}{c^3}\frac{M_1 M_2}{M_1 + M_2}\frac{1}{a^3},$$

   where M_1 and M_2 are the masses of the two stars. Obtain the values of the relevant parameters for the - a) Hulse-Taylor system, b) double pulsar system. Given that the orbit of the Hulse-Taylor system is shrinking by 1mm / year and that of the double pulsar system is shrinking by 7mm/day, estimate the time left for these systems before merger by integrating the above equation.

4. **Accretion Energy**

   Assume the efficiency of energy release (the amount of potential energy converted to electromagnetic radiation), when a particle falls into the gravitational potential of a massive object, to be $\sim 10\%$. Calculate the energy released if a proton falls (from infinity) into the gravitational potential of - the Earth, the Sun, a White Dwarf and a Neutron Star. Find the frequency of radiation in each case.

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