Review of Low Energy Nuclear Astrophysics

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Abstract

In this review of Low Energy Nuclear Astrophysics we review the nuclear energy and evolution of the sun. Then we review the estimate of dark matter from galaxy rotation. Next we discuss neutron star formation from the gravitational collapse of massive stars which produces neutron stars and their velocity. Then origin of supernovae, the estimate of dark energy from supernovae acceleration, and experiments related to low energy nuclear astrophysics are reviewed.

1 Introduction

Recently trends in Nuclear Astrophysics have been reviewed [1]. Since we shall be reviewing dark matter and dark energy, one should note that Cosmic Microwave Background Radiation (CMBR) experiments, e.g. Ref [2], estimated the amount of dark energy and dark matter in the universe. More recent dark matter detection experiments are DarkSide [3], XENONIT [4] and CDEX [5]. Recent estimates are:

$$\begin{aligned} \text{Dark Energy Density (vacuum energy)} &\simeq 0.73 \\ \text{Dark Matter Density} &\simeq 0.24\ . \end{aligned} \tag{1}$$

In the following section we review nuclear reactions providing energy for the sun and the evolution of the sun. Next we review the first detection of of Dark matter about a century ago from the rotational velocity of our Milky Way Galaxy.

In the next section we review the collapse of massive stars with the production of neutron stars and black holes. Since the neutron stars have a magnetic field and they are rotating they emit electromagnetic radiation, and are called pulsars. We review the origin and magnitude of the velocity of pulsars.

In the next section we discuss the formation of supernovae and how the amount of dark energy in the universe can be estimated from the velocities of supernovae, and compare these measurements to the CMBR measurements given above in Eq(1).

In our final section we discuss experiments related to low energy nuclear astrophysics.

2 Nuclear Energy and the Evolution of the Sun

About 5 billion years our sun was a cloud of dust. Gravity collapsed the material in on itself as it began to spin. Small particles drew together, bound by the force of gravity, into larger particles, and about 4.6 billion years ago our sun was formed.

Nuclear Enerrgy produces outward pressure stoppung the gravitational collapse of the sun. Nuclear Enerrgy starts with proton-proton reactions: H^1, H^2, He=Proton, Duterium, Helium):

$$\begin{aligned} H^1 + H^1 &\rightarrow H^2 + \text{ positron } + \text{ neutrino} \\ H^1 + H^2 &\rightarrow He^3 + \text{ energy} \\ He^3 + He^3 &\rightarrow He^4 + H^1 + H^1 + \text{ energy}\ . \end{aligned}$$

These nuclear reactions are followed by Helium fusion

$$\begin{aligned} He^4 + He^4 &\rightarrow Be^8 + \text{ energy} \\ Be^8 + He^4 &\rightarrow C^{12} + \text{ energy} . \end{aligned}$$

Another chain is the CNO cycle, in which Carbon C^{12} serves as a catalyst. This CNO cycle can be represented by:

$$C^{12} + 4(H^1) \rightarrow C^{12} + He^4 + \text{ 2positrons } + \text{2neutrinos} + \text{ energy} ,$$

where a positron is an anti-electron, with positive electric charge.

In about 5 billion more years our our aging sun will develope a core and envelope that do not burn. A hydrogen shell developes that burns and expands our aging sun into a red giant. This red giant will be so large that it will cover our earth.

3 Galaxy Rotation and Dark Matter

Our galaxy, the Milky Way, is a gargantuan collection of stars, gas, dust, with a massive black hole (which we discuss in the next section) held together by gravity. Gravity does not collapse due to the centripital force. An object with mass,m, rotating with speed v at a radius R from the center has the centripital force F_c

$$F_c = m\frac{v^2}{R} \tag{2}$$

By measuring the galaxy radius, its speed, and the amount of visible mass, the amount of dark matter mass can be estimated. this is illustrated in Figure 1 below.

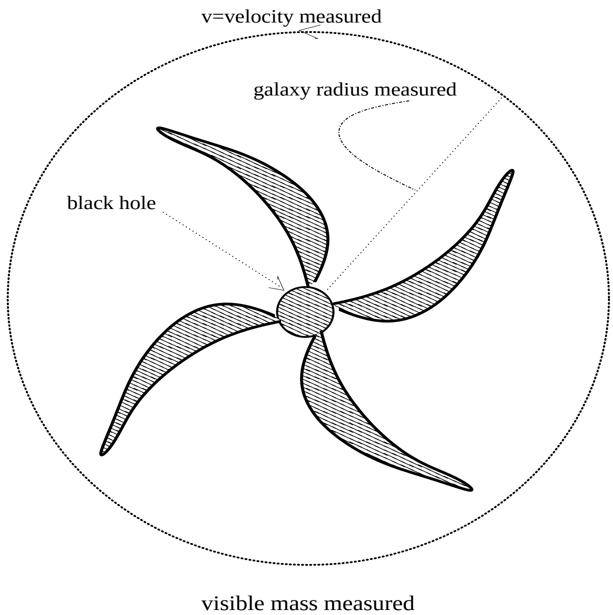

Figure 1: Milky Way galaxy radius, velocity, visible mass measured

From the measurements illustrated in Figure 1 it is now estimated that about 95 % of the Milky Way galaxy mass is dark matter, however this includes the mass of the massive black hole at the enter of the galaxy. Therefore these measurements of the Milky Way galaxy mass are consistent with Eq(1).

The essential property of dark matter particles is that their only interaction is gravitational. There have been many attempts to determine dark matter mass (or masses, as there might more than one dark matter particle). For example in Ref [6] there were attempts to constrain the mass of dark matter particles by measuring the antiproton to proton ratio in cosmic rays.

When the first estimates of dark matter mass were carried out almost a century ago the concept of dark matter. Except for black holes the nature of dark matter is still a mystery.

4 Neutron Stars, Black Holes, and Pulsars

Massive Stars, M $>\sim 8 \times M_{sun}$, where the mass of the sun $M_{sun} \simeq 2.010^{30}$ kg, burn their nuclear fuel quickly. They collapse to density 10^{14} g cm^{-3} >, which is nuclear density. A protoneutron star formed in $\sim$ 0.01 s. Because of the high density neutrinos are trapped in neutrinosphere, with radius of $\sim$ 40 km.

From 0.1 to 10 sec the neutrinosphere contracts from $\sim$ 40 km to protostar radius $\sim$ 10 km. Antineutrinos, $\bar{\nu}_e$ carry energy from the emerging star via URCA process

$$n \quad \rightarrow \quad p + e^- + \bar{\nu}_e \ .$$

From $\sim$ 10 to $\sim$ 50 sec n-n collisions dominate neutrino production via the modified URCA process

$$n + n \quad \rightarrow \quad n + p + e^- + \bar{\nu}_e \ .$$

The final start has a rsdius of about 10 km. If it's mass is greater than 1.5 M_{sun} it continues to collapse to become a black hole. Since (using Einstein's General Theory of Relativity) spcace is curved around a black and no light can be emitted, which is why it is called a black hole. If the mass is less than 1.5 M_{sun} it becomes a neutron star.

The neutron star has a large magnetic field (arising from the original star's magnetic field), and spins very fast conservation of angular momentum. This rapidlt spinning magnetic field sends out electromagnetic radiation: it is a pulsar.

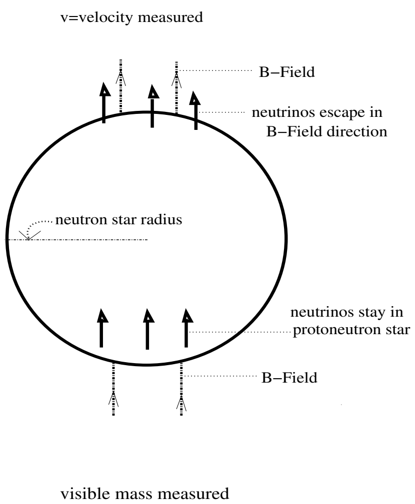

Figure 2: pulsar receives velosity via neutrinos and emits electromagnetic rediation via spinning B field

Due to the neutrinos captured by the protoneutron star, as shown in Figure 2, the pulsar gains a velocity. With the temperature, T, of the neutron star about 10^{10} K, the velocity,v, is about 200 km/s. Pulsar velocities with a range of velocities $20km/s \geq v \leq 10,000km/s$, depending on luminoscity, were predicted [7, 8] and this been confirmed by measurements of the electromagnetic rediation of pulsars.

5 Mass of Neutron Stars and Central Density

Recently an article "Covariant Density Functional Theory in Nuclear Physics and Astrophysics"[9] derived how the Mass of Neutron Stars depend on nuclear density.

This article explained how experiments[10, 11] provided critical information for fundamental parameters of the equation of state for theorists to estimate the relationship between the mass of a neutron star and the central density of the neutron star.

However recent experiments[12, 13] have shown that the results published in Refs[10, 11] have more uncertainty that expected.

The results from Ref[9] are shown in the Figure 3 below

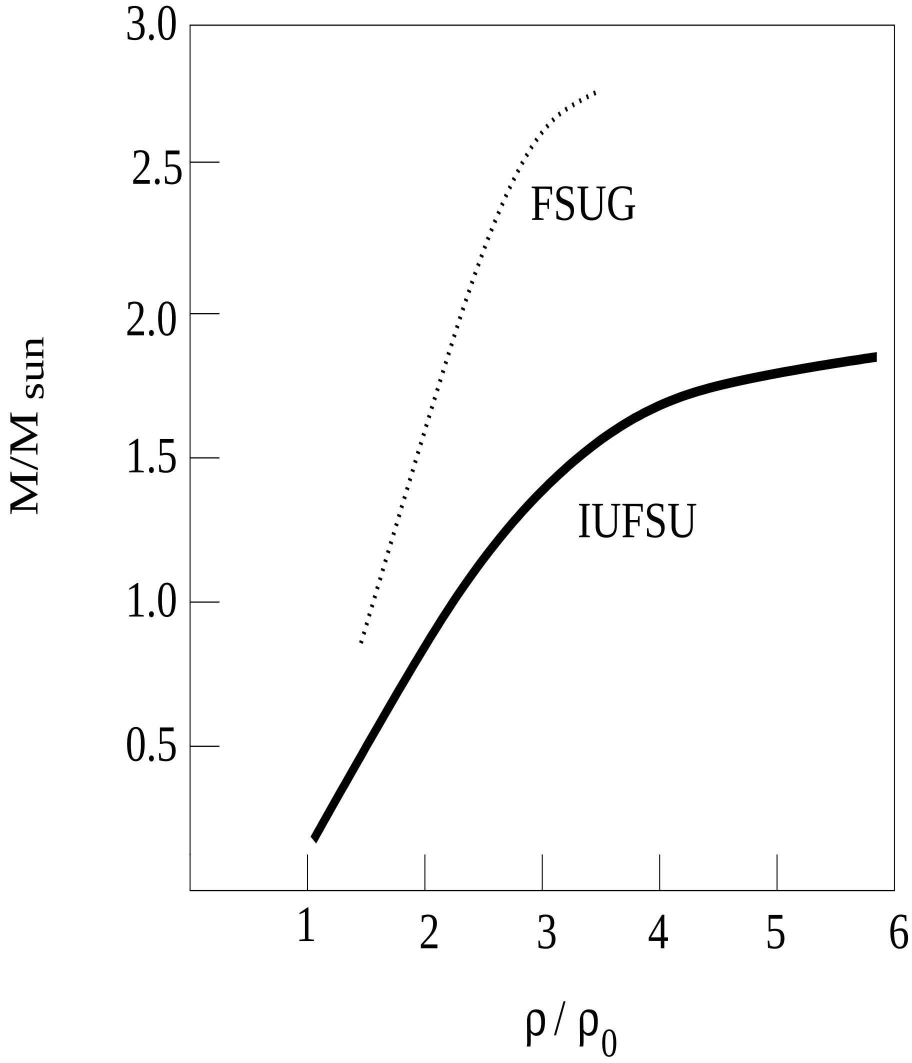

Figure 3: Relationship between the ratio of mass of a neutron star to the mass of the sun and the rato central density to the minimum central density of a neutron star

The curve FSUG for M/M_{sun} was derived using the FSUGold model[14].

The curve IUFSU for M/M_{sun}, derived by Yang and Piekarewicz in Ref[9], is the most recent and probably most accurate theoretical calculation of M/M_{sun} vs ρ/ρ_0, with ρ_0 the minimum central density of a neutron star.

6 Supernovae and Dark Energy

Some massive stars collapse and explode emitting bright light. They are called supernovae.

As Hubble determined about one century ago that the Universe is expanding by measuring redshifts of light from known atoms, the velocity of supernovae has been measured for supernovae at various distances using redsifts of light from supernovae.

The Supervova Cosmology Project [15] carried our many measurements of redshifts of light from supernovae, with redshifts between 0.18 and 0.83. This is illustrated in Figure 3

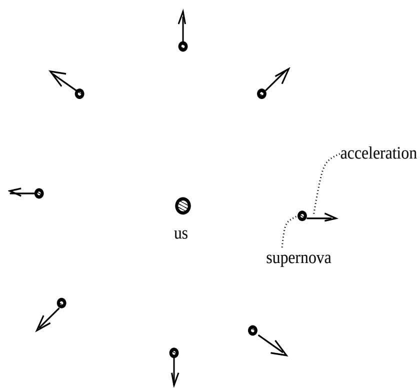

Figure 4: Measurements of acceleration of supernovae to determine redshifts and dark energy density in the universe

From the results in Ref [15] and other studies of supernovae redshifts it was determined that Dark Energy Density (vacuum energy) is $\simeq 0.70$, in agreement with CMBR measurements shown in Eq(1)

7 Experiments Related to Low Energy Nuclear Astrophysics

The nuclear physics experiments have contributed towards the understanding of nuclear astrophysics [16, 17]. The varied experimental methods using stable-isotope beams via transfer reactions and scattering have helped in the understanding of the astro-physically significant states of radioactive nuclei. Also low-intensity radioactive beams have furthered the knowledge of transfer reactions indirectly. But such reactions need to be explored more with advanced detectors and better radioactive beams. The Radioactive ion beams can provide research capabilities which are un-available with ordinary ion beams. In particular, radioactive beams allow investigation of nuclear reactions important to the stellar burning and nucleosynthesis which occur in high temperature and/or density environments in stars. Also photon beams which seem to provide new avenues [16, 17].

Further experimental setups when in deep underground laboratories can help in background reduction and control [16, 17]. Underground facilities engaged in this search are the LUNA project at the Laboratori Nazionali di Gran Sasso of INFN, in Gran Sasso, Italy [18], and Compact Accelerator System for Performing Astrophysical Research (CASPAR) with a low energy accelerator [19].

Among the experimental facilities which are engaged towards direct detection methodologies are at Laboratory for Experimental Nuclear Astrophysics (LENA) at the Triangle Universities Nuclear Laboratory (TUNL) [16, 17].

New facilities with the tandetron accelerators [20, 21] are coming up for further astrophysical measurements. New and advanced detection methods like active-target detectors, AT-TPC, have been developed for measurements of astrophysical reaction rates with charged particles [16, 17, 22].

8 Conclusions

We have reviewed many essential aspects of low energy nuclear astrophysics.

We reviewed the nuclear reactions which provide the energy in the sun, and how in about 5 billion years the sun will become a red giant. Then the first discovery of dark matter almost a century ago by measuring the rotational velocity and visible mass in our Milky Way Galaxy, with results consistent with CMBR measurements, was discussed.

Then the creation of neutron stars and black holes by the collapse of massive stars was discussed. The creation of velocity of neutron stars by neutrinos escaping in the direction of the strong magnetic field producing pulsars was reviewed. Also, the mass of neutron stars as a function of central density was reviewed.

The measurement of the amount of dark energy in the universe by measuring the redsift of light from supernovae at various didtances from us was reviewed. The result that Dark Energy Density is $\simeq 0.70$, in agreement with CMBR measurements, was discussed.

Finally, experiments related to Low Energy Nuclear Astrophysics were discussed, with explanations of how various experiments with different setups can measure various aspects of nuclear astrophysics. ons.

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