

Neutrinos and the synthesis of heavy elements: the role of gravity

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Abstract. The synthesis of heavy elements in the Universe presents several challenges. From one side the astrophysical site is still undetermined and on other hand the input from nuclear physics requires the knowledge of properties of exotic nuclei, some of them perhaps accessible in ion beam facilities. Black hole accretion disks have been proposed as possible r-process sites. Analogously to Supernovae these objects emit huge amounts of neutrinos. We discuss the neutrino emission from black hole accretion disks. In particular we show the influence that the black hole strong gravitational field has on changing the electron fraction relevant to the synthesis of elements.

1 Introduction

Where and how heavy elements are produced in the Universe is one of the fundamental questions in science. Attempting to answer it requires efforts from different fields. From one side, astronomical observations provide information about the abundances of heavy elements, while nuclear physics brings insight on the details of the reactions taking place among nuclei and that result in some final abundances. The goal is to be able to emulate the thermodynamical conditions of some stellar site, to evolve a reaction network under those conditions, and finally to reproduce the observed abundaces. However, at this point, there is still controversy on the astronomical site(s), and the nuclear properties of many of the nuclei participating in the reactions are uncertain. New experimental facilities bring hope in the study of nuclei far from stability (e.g. [1–3]). These studies will also shed light on theoretical models, needed to determine the properties of perhaps never accesible nuclei.

Among all these different ingredients, neutrinos play a crucial role. Via weak interactions they can drive a medium proton-rich or neutron-rich. This together with the thermodynamical evolution of the matter determine what kind of elements are synthetized. The flux of neutrinos emitted from stellar sources such as supernovae and black hole accretion disks (two of the suggested sites of r-process nucleosynthesis), can be affected by different kind of physics, e.g flavor oscillations [4,5] and coherent scattering [6,7]. In previous works [8,9], we have studied the influence that gravity has on the emission of neutrinos and the production of heavy elements in outflows emerging from black hole accretion disks. Although our studies have been focused on these particular sites, the effects of strong gravitational fields on neutrino emission are important in any other enviroment where neutrinos are copiously produced in the vicinity of massive central object. Of particular importance is the consideration of the 3D geometry of the source, as the relativistic effects depend on the space-time curvature. Below we discuss some more details of the effect of general relativity on neutrino fluxes and the synthesis of heavy elements in black hole accretion disks.

2 General Relativistic Effects on Neutrino Fluxes

The strong gravitational field generated by a compact object changes the geometry of the space-time around it. This affects the flux of neutrinos observed at a certain distant from the central object. The main effects of the gravitational field on the fluxes are the shifts of energies and the deformation of the solid angle that the source subtends as seen by the observer $d\Omega_{ob}$. The latter can be determined via the deflection of the neutrino trajectories and requires to find their null geodesics in a given curvature. The emitted energy $E_{em}$ and the observed energy $E_{ob}$ are related by $E_{em} = (1+z)E_{ob}$ where $(1+z)$ is the redshift.

The effective neutrino flux observed at some distance $r_{ob}$ from the compact object is

$$\phi^{\text{eff}} = \frac{1}{4\pi} \int d\Omega_{ob} \times \phi_{ob}(E_{ob}).$$  \hspace{1cm} (1)

The starting point to perform a transformation from the fluxes in a flat geometry (here we call them Newtonian...
fluxes) to the ones in a curved one (General Relativistic
fluxes) is the conservation of the number density in phase space [10]. This leads to write the observed general relativistic fluxes as
\[
\phi^{\nu}_{eff} \propto \frac{1}{4\pi} \int d\Omega_{\nu} \times \frac{E_{\nu}^2}{\exp(E_{\nu}(1+z)/T_{em}) + 1},
\]
(2)
where have written the neutrino Fermi-Dirac distribution in terms of the temperature at the emission point \(T_{em}\) (usually the known amount from numerical simulations). Both the redshift \(1+z\) and and the solid angle \(d\Omega_{\nu}\) depend on the space-time geometry, and therefore on the details of the matter distribution of the compact object.

3 Reaction rates
A key factor in determining the type of nuclear products synthetized in a astrophyscial site (particularly in neutrino-driven like environments) is the proton to neutron fraction or electron fraction \(Y_e\). If \(Y_e > 0.5\) the medium is proton-rich while if \(Y_e < 0.5\) it is neutron-rich. In this kind of environments the initial thermodynamical conditions of the matter surrounding the compact object are such that this is dissociated into electron, protons and neutrons. Then, the main reactions setting the matter composition are:
\[
e^+ + n \leftrightarrow p + \bar{\nu}_e, \quad (3)
\]
\[
e^- + p \leftrightarrow n + \nu_e. \quad (4)
\]
If the flux of electron neutrinos is larger than the electron antineutrinos the inverse reaction of equation (4) will drive the matter proton rich. Conversely, if the electron antineutrino flux is larger then the matter will be neutron rich. On the other side, if both neutrino and antineutrino fluxes are weak the forward reactions, electron capture on protons and positron captures on neutrons, will play a more important role than neutrinos in determining the electron fraction.

The electron fraction \(Y_e\) that is obtained by taking into account only the reverse reactions of eqs. (3 and 4) depends on the absorption rates of these processes. As the neutrino fluxes, which determine the reaction rates, are affected by a strong gravitational field, \(Y_e\) is also affected. In terms of the observed fluxes \(\phi^{\nu}_{eff}\) (eq. 2) the rate of absorption of neutrinos on neutrons is
\[
\lambda_{\nu,n} = b \int_{E_{\nu min}}^{E_{\nu max}} \phi^{\nu}_{eff} (E_{\nu} + \Delta)^2 \left[1 - \frac{m_e^2}{(E_{\nu} + \Delta)^2}\right] dE_{\nu},
\]
and of antineutrinos on protons
\[
\lambda_{\bar{\nu},p} = b \int_{E_{\bar{\nu} min}}^{E_{\bar{\nu} max}} \phi^{\bar{\nu}}_{eff} (E_{\bar{\nu}} - \Delta)^2 \left[1 - \frac{m_e^2}{(E_{\bar{\nu}} - \Delta)^2}\right] dE_{\bar{\nu}},
\]
(5)
where \(W_M = 1 + 1.1 E_{\nu}/m_n\) and \(W_M = 1 - 7.1 E_{\bar{\nu}}/m_p\) are the weak magnetism corrections [10]. \(m_n, m_p\) are the neutron and electron masses respectively. \(\Delta\) is the neutron-proton mass difference, and \(b = 9.704 \times 10^{-50}\) cm² keV⁻².

4 Astrophysical site: Accretion disk outflows
A possible scenario after the merger of two compact objects (black hole-neutron star or neutron star-neutron star) is the formation of an accretion disk or torus around a black hole. Given the initial conditions of the progenitors the matter of disk is neutron rich and hot enough to be dissociated in nucleons. Some fraction of this matter can be ejected in hot outflows, presenting an interesting scenario for the synthesis of neutron-rich elements.

The results presented here and on ref. [8] are based on a time dependent hydrodynamical simulation of accreting matter around a 3 solar masses black hole with a spin \(a = 0.8\) (for more details on the simulation see [11]). In this scenario neutrinos are copiously emitted. The emission points correspond to the neutrino surfaces, the places where after being trapped by the high density conditions, neutrinos can freely travel. Figure 1 shows a transversal cut of the electron neutrino and antineutrino surfaces for this disk model at \(t = 20\) ms. The \(z\) axis correspond to the actual decoupling height, and the colored scale shows the neutrino temperature \(T_{em}\), which is crucial in calculating the neutrino fluxes as described in eq. 2. The reactions and details used to calculate these surfaces are discussed in ref. [12]. The difference in the neutrino decoupling surfaces for each flavor, in energy and in distance from the black hole, has important consequences in terms of the effects of gravity on nucleosynthesis.

For the outflow we adopt standard neutrino-driven wind trajectories parameterized in entropy and timescale or acceleration. See for example ref. [13] for supernova and ref. [14] for accretion disk outflows. Our outflow follows a radial streamline that starts at \(r = 30\) km from the black hole and extends to thousands of kilometers away. Figure 2 shows the electron antineutrino surfaces at two different times \(t = 20\) and 60 ms, and a segment of the outflow trajectory (magenta line). As time passes and material is dragged into the black hole the neutrino surfaces shrink.
4.1 Neutrino fluxes

We calculate the neutrino fluxes for this astrophysical environment, as in eq. 2. The observers are the points of the outflow trajectory where the reactions of eqs. 3 and 4 take place. The emitters are the points on the neutrino surfaces.

For each point in the outflow we find the null geodesics that connect them to each point on the neutrino surface. This procedure determines the solid angles \( d\Omega_{ob} \). The redshift \( 1+z \) also depends on the position of the outflow trajectory \( r_{ob} \) and on the emission points on the neutrino surface \( r_{em} \). We calculate both redshifts and null geodesics in the Schwarzschild metric in a similar way as in ref. [9].

At \( t = 20 \text{ ms} \) electron antineutrinos are hotter (see colored scale in figure 1) and their fluxes are larger than electron neutrino fluxes. This is true regardless of the space-time curvature, as can been seen when we compare the fluxes by flavor in figure 3 (black vs red lines), where we have plotted the fluxes seen at \( z = x = 100 \text{ km} \). This difference result in more antineutrino captures on protons, driving the material neutron rich. When general relativistic effects are included the more energetic antineutrinos that are emitted closer to the black hole are more redshifted than the neutrinos. This causes the large energy tails of the fluxes to be reduced (compare dotted-dashed lines for Newtonian (N) neutrinos with solid lines for the relativistic ones (GR) in figure 3). As a result in a curved space-time the electron antineutrinos capture rates are more reduced when compared to the Newtonian rates and the material becomes less neutron rich than the neutrinos that are emitted closer to the black hole. As an example for an outflow trajectory with an entropy per baryon of 30, the Newtonian electron fraction \( \tilde{Y}_e \) tends to 0.47 near \( z = x = 100 \text{ km} \), while the relativistic is \( \tilde{Y}_e \approx 0.49 \) (for an illustration of the behavior of electron fraction, with a specific outflow, with and without general relativity see figure 2 of ref. [8]).

Note however, that the dynamical evolution changes the emission points as is shown in figure 2. Then the time dependence of the neutrino surfaces plays an important role. Figure 3 shows the neutrino fluxes at two different times \( t = 20 \text{ ms} \) (red lines) and \( t = 60 \text{ ms} \) (blue lines) as seen by an observer located at \( x_{ob} = z_{ob} = 100 \text{ km} \) from the black hole. At \( t = 20 \text{ ms} \) electron antineutrino fluxes are larger than the electron neutrino fluxes, as it was discussed above (compare solid vs dashed red lines). However, we see the opposite behavior at \( t = 60 \text{ ms} \) (see blue lines in figure 4): the electron neutrino fluxes are larger. This is because as time passes more material has been dragged into the black hole, and although both surfaces shrink, the electron antineutrino one is much more reduced. As a result at \( t = 60 \text{ ms} \), neutrino capture on neutrons (eq. 4) dominates and the material becomes proton rich. When general relativity is taken into account the reduction of the antineutrino fluxes is stronger because the antineutrinos are even more redshifted than neutrinos. This makes the medium even more proton rich. In the example mentioned above this translates into a Newtonian \( \tilde{Y}_e \approx 0.53 \), while with GR \( \tilde{Y}_e \approx 0.56 \) (this can be seen in the magenta lines of figure in ref [8]).
with GR corrections would lead to $Y_e$ Note however, that for higher entropies, the simulations richness of the outflow, by increasing the electron fraction.

The flux of neutrinos observed from a source with a massive central object is significantly different from the flux emitted from the same source in a gravitational field free space. This difference affects the neutrino absorption rates on nucleons and therefore the electron fraction of the medium. The changes introduced in the electron fraction by the gravitational field are important enough to alter the nucleosynthesis final abundances.

Due to the initially low electron fraction of their progenitors, merger-type accretion disks have been considered to be good candidates for the synthesis of heavy neutron rich nuclei. We study the synthesis of elements that occur in black hole accretion disk outflows. Our disk model is based on a hydrodynamical simulation, and the outflow model is similar to standard supernova neutrino winds. We find that gravity plays an important role in setting the electron fraction via its influence in the behavior of neutrinos. The over all change in the neutrino fluxes is a reduction of the high energy tails due to redshifts. This effect is stronger in the electron antineutrino channel, driving the material proton-rich. We find that time evolution plays an important role as the neutrino surfaces shrink when matter is dragged into the black hole. This reduction in the neutrino surfaces combined with the stronger redshifts leads to even more proton rich material and the synthesis of larger amounts of $^{56}$Ni for a wide range of outflow conditions.

6 Conclusions

The flux of neutrinos observed from a source with a massive central object is significantly different from the flux emitted from the same source in a gravitational field free space. This difference affects the neutrino absorption rates on nucleons and therefore the electron fraction of the medium. The changes introduced in the electron fraction by the gravitational field are important enough to alter the nucleosynthesis final abundances.

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