PROCEEDINGS OF SCIENCE

Nucleosynthesis from Black Hole Accretion Disks

Gail Mclaughlin*†
North Carolina State University
E-mail: Gail_McLaughlin@ncsu.edu

Liliana Caballero
North Carolina State University
E-mail: olcaball@ncsu.edu

Rebecca Surman
Union College
E-mail: surmanr@union.edu

Rapidly accreting disks surrounding black holes can form in compact object mergers or long duration gamma ray bursts. Several types of nucleosynthesis occur in hot outflows from these objects, including an r-process, p-process and significant production of Nickel-56. Neutrinos play a pivotal role in all of these processes. We outline these with comments on general relativistic corrections for the neutrinos, and "collective" flavor transformations of neutrinos from hot dense environments.

11th Symposium on Nuclei in the Cosmos, NIC XI
July 19-23, 2010
Heidelberg, Germany

*Speaker.

†This work was partially supported by the Department of Energy under contracts DE-FG02-02ER41216 (GCM) and DE-FG05-05ER41398 (RS)

PoS(NIC XI)031

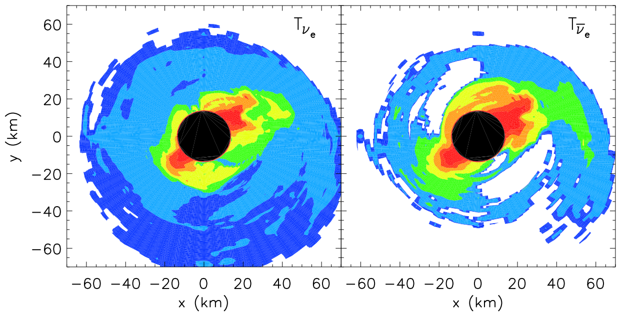

Figure 1: Shows the spectra of emitted neutrino spectra from a black hole neutron star merger. Colors represent temperatures of emitted neutrinos from hottest, T = 11 MeV - red, to coolest, T = 1 MeV (light blue). Figure from [6]

1. Introduction

Black hole accretion disks occur in many different types of astrophysical environments. Disks that are hot enough to photo-dissociate nuclei are thought to occur in compact object mergers, some core collapse supernovae with rotating progenitors and also in gamma ray bursts, e.g. [1, 2]. These disks have "hot" non relativistic outflow, as well as colder outflows [3] , or material that becomes unbound from tidal tails, e.g. [4]. In the hot outflow, material from the disks begins in free neutrons and protons, and as it flows away from the disk forms nuclei. The nuclei that form are dependent on the accretion rate of the disk and on the neutrinos that are released from it [5]. Rapidly accreting disks characteristic of neutron star mergers are most likely to produce rapid neutron capture elements in hot outflows [6], while more slowly accreting disks are more likely to produce Nickel-56 or p-process elements [5, 7, 8]. Since the neutrinos are crucial for understanding the the nucleosynthetic products, in this contribution we consider two neutrino effects. First we discuss the consequences of gravitational bending of the neutrinos, and then we briefly consider neutrino flavor transformation.

2. Discussion

Fig. 1 shows a disk formed by a black hole neutron star merger, calculated in [6, 9]. Above the disk, the emitted neutrinos interact with material outflowing from the disk through the reactions $\nu_e + n \rightarrow p + e^-$ and $\bar{\nu}_e + p \rightarrow n + e^+$. This strongly influences the neutron to proton ratio in the outflow, and thus the final nuclear products. Fig. 2 shows the nucleosynthetic outcomes that occur from a variety of possible outflow trajectories from the disk. As can be seen in the figure, hot outflows from this disk produce at least a weak r-process and possibly also a main r-process. However, these calculations included neither the effect of gravitational red-shift and trajectory bending on the neutrinos, nor the effect of oscillations.

In Fig. 3 we show how the neutrino spectra at a particular point above the disk change when various general relativistic corrections have been applied to neutrinos above the disk shown in Fig. 1. We compare the spectrum without general relativistic corrections (solid line) with the

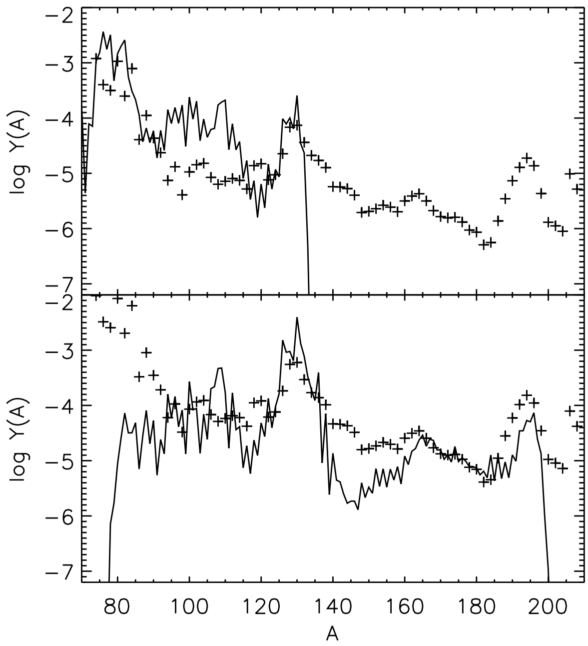

Figure 2: Shows nucleosynthesis from trajectories originating from the disk in Fig. 1. A variety of outflow timescales and entropies were studied [6] and in all cases a weak or a main r-process was found. Figure from [6]. Crosses represent solar data while the solid line represents the abundance pattern obtained in the calculation.

spectrum when only the gravitational redshift is taken into account (short dashed red line) and the spectrum when geodesic tracing has been performed and the energy redshift is taken into account (blue dashed line). For the blue dotted line, the effect of disk rotation was added. Due to the asymmetry of the disk, this last effect is highly dependent on disk angle. It can be seen that not only the redshift correction but also trajectory bending (geodesic tracing) must be included in order to predict accurate spectra. Due to the asymmetry of the disk, the effect of disk rotation (Ω) can have a different sign depending on the position above the disk.

In Fig. 4, we show the impact of these corrections on the abundance pattern. The crosses show the data, and the purple line shows the calculation without the inclusion of general relativistic effects. The red line shows the results when only energy redshift has been taken into account. The blue line shows the effect when both geodesic tracing and energy redshift have been taken into account. In general the trend is to drive the material in the outflow less neutron rich. The neutron richness is due to an antineutrino flux which is hotter than the neutrino flux and emitted closer to the center of the disk. Thus the antineutrinos are “corrected” more than the neutrinos, and the outflow loses some of its neutron richness.

We also consider the impact of flavor transformation. The disk geometry is at present beyond the state of the art in neutrino flavor transformation calculations, so we consider a simplified spherical geometry. In Fig. 5 we show a schematic calculation with a sample trajectory together with a flavor transformation probability of electron neutrinos. In this figure, the flavor transformation

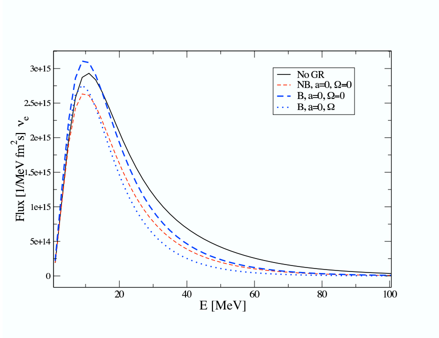

Figure 3: Shows the change in neutrino spectra at a point above this disk when various GR corrections have been applied. The lines are explained in the text. Figure provided by Liliana Caballero.

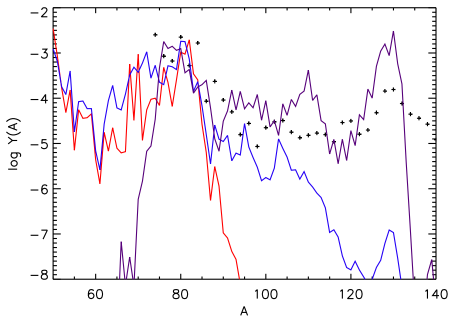

Figure 4: Shows the change in abundances in a hot outflow from this disk when various GR corrections have been applied to the neutrino spectra. Crosses show the data and the lines are explained in the text. Figure by Rebecca Surman.

takes place at the point where the seeds begin to form. To get more quantitative results, we take a calculation similar to that presented in [10], and combine it with a reaction network calculation. The results for the abundance pattern are shown in Figure 6. The calculation is based on the following conditions: $s/k = 200$, initial timescale $\tau = 25\,\mathrm{ms}$, $T_{\nu_e} = 2.6\,\mathrm{MeV}$, $T_{\bar{\nu}_e} = 4.0\,\mathrm{MeV}$, $L_{\nu_e} = 6.6\times 10^{51}\mathrm{ergs\,s^{-1}}$, $L_{\bar{\nu}_e} = 8.8\times 10^{51}\mathrm{erg\,s^{-1}}$, $L_{\nu_\mu} = 12.7\times 10^{51}\,\mathrm{erg\,s^{-1}}$ The crosses show the solar data. The purple line shows the calculation without neutrino interactions. The blue line shows the calculation with neutrino interactions included, but no oscillations. The yellow line shows the result neutrino flavor transformation with the "single angle" approximation. The green line shows the result with the full multi-angle calculation.

3. Conclusions

Neutrinos have a significant impact on nucleosynthesis from hot outflows. Hot outflows from black hole accretion disks produce a variety of elements from ^{56}Ni to the r-process elements. Since the neutrinos play a crucial role in determining the relative numbers of neutrons to protons, the neutrino spectra must be well understood. We have shown that there are two types effects which stem from general relativity and from flavor transformation, that influence the final nucleosynthetic yields in this astrophysical environment. In both cases, these corrections make neutron rich outflow less neutron rich.

References

[1] A. MacFadyen and S. E. Woosley, Astrophys. J. **524**, 262 (1999) [arXiv:astro-ph/9810274].

[2] M. Ruffert and H. T. Janka, Astron. Astrophys. **344**, 573 (1999) [arXiv:astro-ph/9809280].

[3] B. D. Metzger *et al.*, arXiv:1001.5029 [astro-ph.HE].

[4] Meyer, B. S., 1989, ApJ **343**, 254.

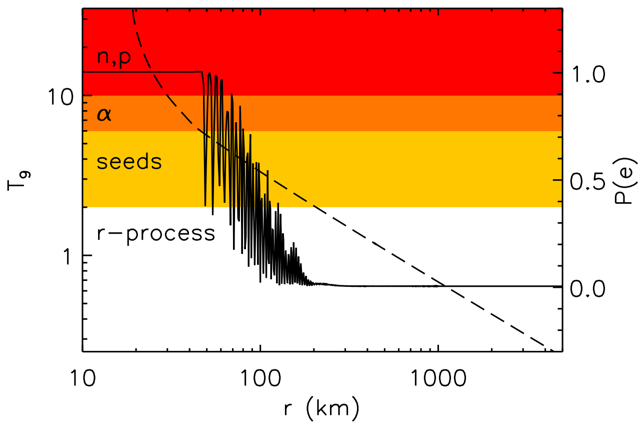

Figure 5: Shows the potential for collective neutrino flavor transformation to influence nucleosynthetic yields in hot outflows. The dashed line shows a sample outflow trajectory and the solid line shows the probability of flavor transformation. Figure by Rebecca Surman.

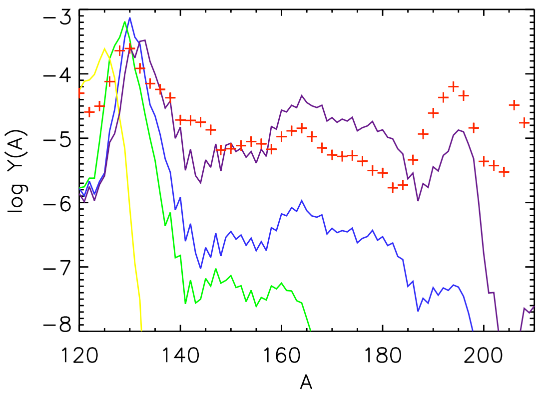

Figure 6: Shows the influence of collective neutrino flavor transformation on r-process nucleosynthesis. The conditions and the lines in the figure are described in the text. Figure by Rebecca Surman, neutrino flavor transformation calculation as in [10].

[5] R. Surman, G. C. McLaughlin and W. R. Hix, Astrophys. J. **643**, 1057 (2006) [arXiv:astro-ph/0509365].

[6] R. Surman, G. C. McLaughlin, M. Ruffert, H. T. Janka and W. R. Hix, Astrophys. J. **679**, L117 (2008) [arXiv:0803.1785 [astro-ph]].

[7] J. Pruet, R. Surman and G. C. McLaughlin, Astrophys. J. **602**, L101 (2004) [arXiv:astro-ph/0309673].

[8] L. T. Kizivat, G. Martinez-Pinedo, K. Langanke, R. Surman and G. C. McLaughlin, Phys. Rev. C **81**, 025802 (2010) [arXiv:1001.3009 [astro-ph.HE]].

[9] O. L. Caballero, G. C. McLaughlin, R. Surman and R. Surman, Phys. Rev. D **80**, 123004 (2009) [arXiv:0910.1385 [astro-ph.HE]].

[10] H. Duan and A. Friedland, arXiv:1006.2359 [hep-ph].