Study of thermal neutrinos in short gamma-ray bursts

G. Morales[(1+)] and N. Fraija[(1*)]
[(1)] Instituto de Astronomía, Universidad Nacional Autónoma de México

Compact object binary mergers; neutron star-neutron star or black hole-neutron star have amply been discussed as progenitors of short gamma-ray bursts (sGRBs). Whereas the strength of magnetic field in a neutron star-black hole merger can be $\sim 10^{12}$ G, in a binary neutron star system, the magnetic field could be amplified beyond $\sim 10^{15}$ G. By calculating the neutrino effective potential up to order M_W^{-4}, we study the emission, propagation, and oscillation of multi MeV-GeV neutrinos in these mergers. In addition, we calculate the neutrino opacity in a GRB event, finding that neutrinos do not escape isotropically but they are collimated in a preferential direction along the jet propagation way. This gives us a powerful tool to discriminate the mechanism by which a GRB is originated. As a particular case, we calculate the number of neutrino events expected on several ground-based neutrino telescopes for the GW170817/GRB170817A event.

1. Introduction

Several lines of evidence have associated the sGRBs progenitors with the merger of compact objects binaries comprised of a binary neutron star (BNS) or a neutron star-black hole (NS-BH) and recent numerical simulations showed that during the merger of a BNS, the existing magnetic field ($\sim 10^{12}$ G) is amplified by several orders of magnitude ($\sim 10^{15}$ G) (Price & Rosswog, 2006).

During the coalescence, a photon-lepton sphere (the so-called fireball) is formed in a compact region in a time scale of the order of seconds which would expand relativistically. In the initial stage, MeV neutrinos are produced mainly by thermal processes (electron-positron annihilation, electron capture on protons, positron capture on neutrons).

2. Propagation, Oscillation and Opacity

In this work, we study the main neutrino properties using the neutrino effective potential (Fraija, 2014) calculated within a fireball with typical values of $T = 3$ MeV, $\mu = 50$ keV, $r = 10^{6.5}$cm. Both merger scenarios have been considered.

3. Results

In Figure 1, we show the strong dependence between the neutrino effective potential and the neutrino propagation angle.

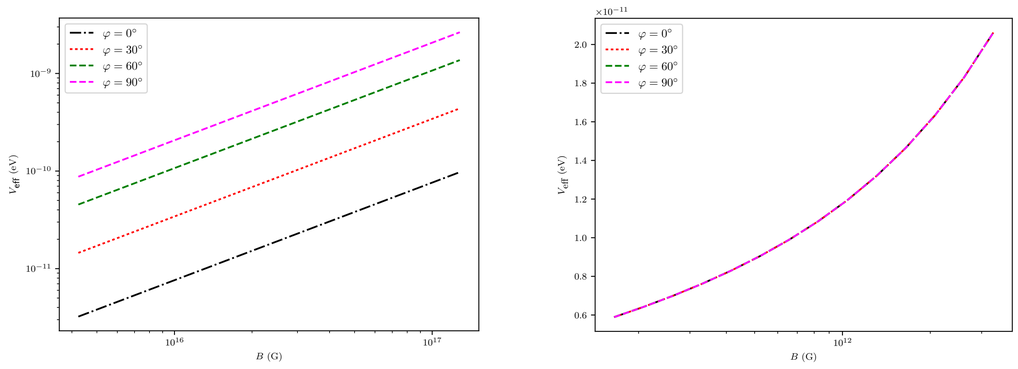

Figure 1. Neutrino effective potential as a function of the neutrino propagation angle for a strong and moderate magnetic field.

The same effect could be verified in Figure 2 where we plot resonance conditions in a BNS merger for neutrinos propagating in parallel as well as perpendicular directions. Neutrino oscillation probabilities for both cases are computed in Figure 3.

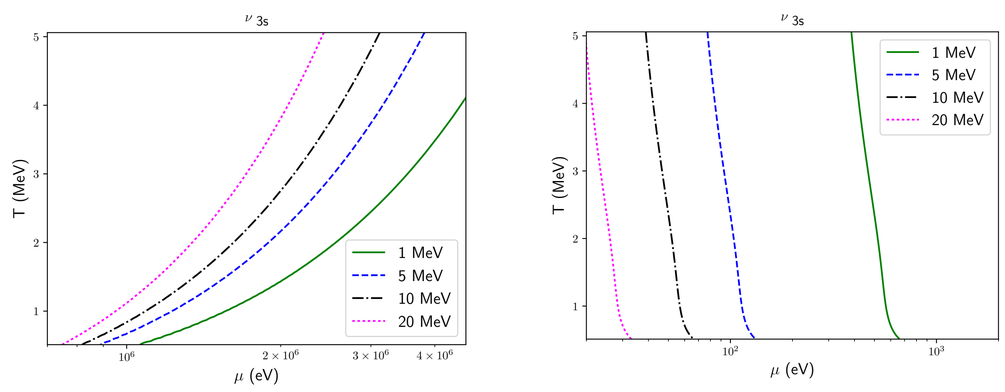

Figure 2. Contour plots of temperature and chemical potential in a BNS merger scenario, using the the global three-flavor neutrinos parameters for which the resonance condition is satisfied. In these plots we have considered a parallel (left) and perpendicular (right) neutrino propagation direction.

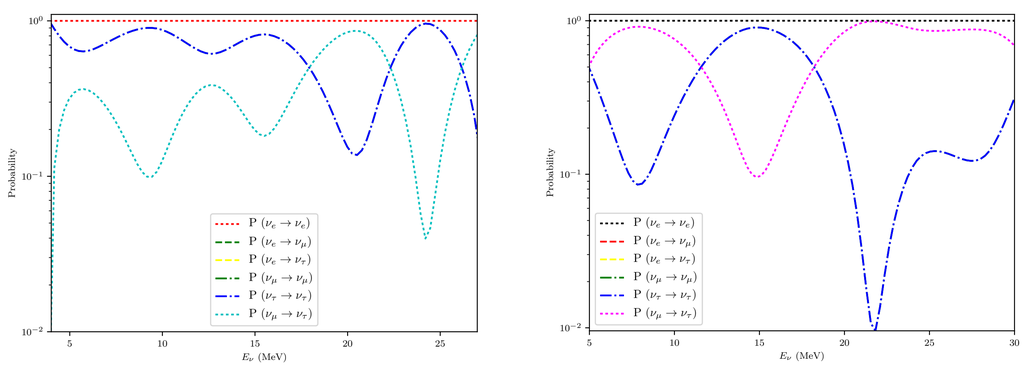

Figure 3. Neutrino oscillation probabilities in a fireball with a strong (left) and moderate (right) magnetic field. In these plots we used the most recent global three-flavor neutrinos parameters reported by (Farzan & Tórtola, 2018).

(+) gmorales@astro.unam.mx
(*) nifraija@astro.unam.mx

We also estimate the neutrino opacity of stellar winds surrounding the central engine taking into account the density profiles (Figure 4) performed through simulations with (Perego, et al., 2014) and without magnetic field amplification (Siegel, et al., 2014).

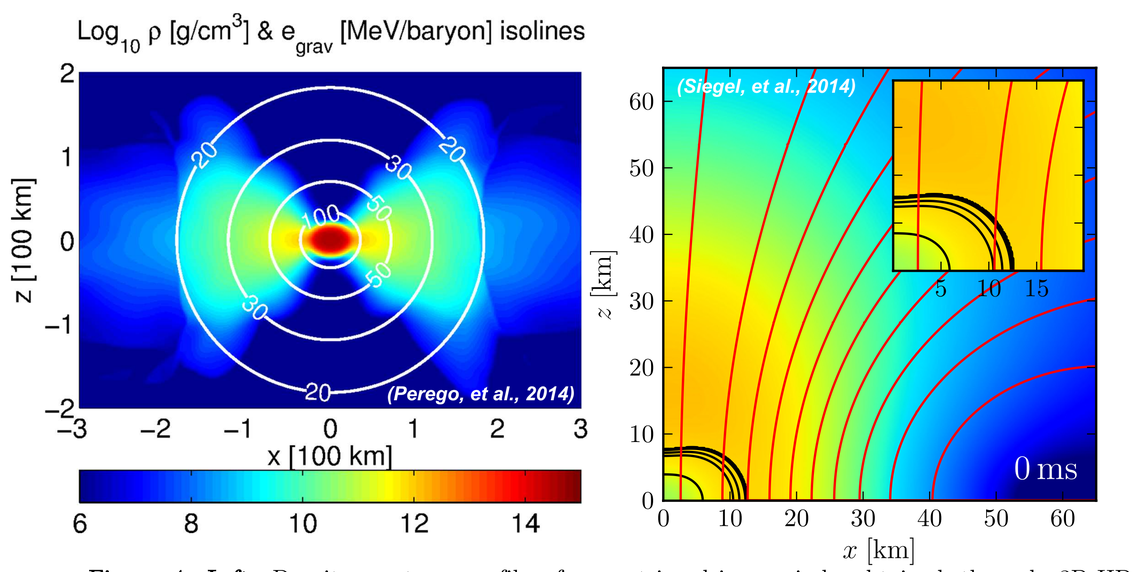

Figure 4. Left: Density contour profiles for neutrino-driven winds obtained through 3D-HD simulations (Perego, et al., 2014). **Right:** Density contour plots for magnetically-driven winds obtained through MHD simulations (Siegel, et al., 2014).

With these density profiles and using a typical MeV-neutrino cross-section of $\sigma_\nu = 5.6\times10^{-41}$ cm^2 (Koers & Wijers, 2005), produced at a characteristic fireball radius of $10^{6.5}$ cm, we plot the neutrino opacity profiles in Figure 5 for both scenarios.

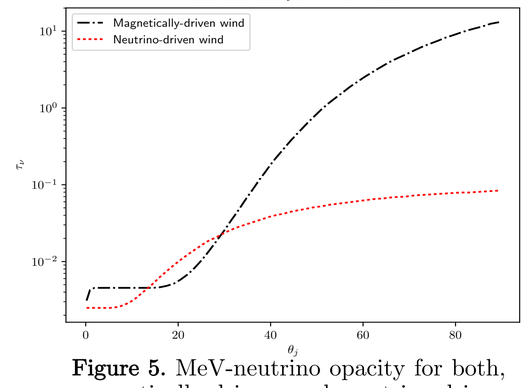

Figure 5. MeV-neutrino opacity for both, magnetically-driven and neutrino-driven wind scenario.

For instance, taking into account a BNS merger event like the GW170817/GRB170817A which had an atypically low energy of $E_{\gamma,iso} \approx 5\times10^{46}$ erg s^{-1} located at 40 Mpc in the galaxy NGC4993, we estimate the arrival of 2×10^{-5} MeV-neutrinos using the future Hyper-Kamiokande detector within a time scale proportional to the prompt emission (2 s), while using IceCube-DeepCore detector we would have expected around 0.15 events for even more energetic neutrinos (GeV range).

4. Conclusions

- Neutrino effective potential is strongly dependent on the magnetic field intensity but also by their propagation angle along magnetic field lines.
- Although neutrino oscillation probabilities are different between both (BNS, BH-NS) scenarios, we do not expect a significant deviation of the standard flavor ratio in ground-based detectors.
- We found that whereas MeV neutrinos leave the central engine almost in an isotropic way due to a neutrino-driven wind, these neutrinos due to magnetically-driven wind can only be detected at viewing angles less than $\sim$50 degrees.
- Using these results, we show an effective criterion to determine which is the most plausible progenitor of sGRBs based on the line of sight of these events.
- We expect to detect the first neutrino from GRBs using the new cubic-kilometer neutrino telescopes.

1. Price, D. J., & Rosswog, S. (2006). Producing ultrastrong magnetic fields in neutron star mergers. Science, 312(5774), 719-722.
2. Fraija, N. (2014). Propagation and neutrino oscillations in the base of a highly magnetized gamma-ray burst fireball flow. The Astrophysical Journal, 787(2), 140.
3. Farzan, Y., & Tórtola, M. (2018). Neutrino oscillations and non-standard interactions. Frontiers in Physics, 6, 10.
4. Perego, A., Rosswog, S., Cabezón, R. M., Korobkin, O., Kaeppeli, R., Arcones, A., & Liebendoerfer, M. (2014). Neutrino-driven winds from neutron star merger remnants. Monthly Notices of the Royal Astronomical Society, 443(4), 3134-3156.
5. Siegel, D. M., Ciolfi, R., & Rezzolla, L. (2014). Magnetically driven winds from differentially rotating neutron stars and X-ray afterglows of short gamma-ray bursts. The Astrophysical Journal Letters, 785(1), L6.
6. Koers, H. B., & Wijers, R. A. (2005). The effect of neutrinos on the initial fireballs in gamma-ray bursts. Monthly Notices of the Royal Astronomical Society, 364(3), 934-942.

We thank CONACyT scholarship (825482) and UNAM-DGAPA-PAPIIT through grant IA102917 for financial support