Instabilities in the time-dependent neutrino disc in Gamma-Ray Bursts

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Abstract

We investigate the properties and evolution of accretion tori formed after the coalescence of two compact objects. At these extreme densities and temperatures, the accreting torus is cooled mainly by neutrino emission produced primarily by electron and positron capture on nucleons (beta reactions). We find that, for sufficiently large accretion rates (>10 M_{Sun}/s), the inner regions of the disk become opaque and develop a viscous and thermal instability. The identification of this instability might be relevant for GRB observations.

Method

We solve numerically for the disc structure in 1D and its time evolution by introducing a detailed treatment of the equation of state. The EOS includes photodisintegration of helium, the condition of beta-equilibrium, and neutrino opacities. We self-consistently calculate the chemical equilibrium in the gas consisting of helium, free protons, neutrons and electron-positron pairs and compute the chemical potentials of the species, as well as the electron fraction throughout the disc.

Hyperaccreting torus in 1D

- Dense, hot torus may form as a result of NS-NS or NS-BH merger or due to the failed SN collapse. Hyperaccreting steady torus optically thin to neutrinos, up to 1 M_{Sun}/s was studied first by Popham, Woosley & Fryer (1999). The neutrino opacities and trapping effect were investigated by DiMatteo, Perna & Narayan (2002). The time evolution of the disk was calculated in Janiuk, Perna, Di Matteo & Czerny (2004). Here, we improve on that model by introducing a much more elaborate equation of state of nuclear matter.

Neutrino emission and absorption mechanisms

Neutronisation

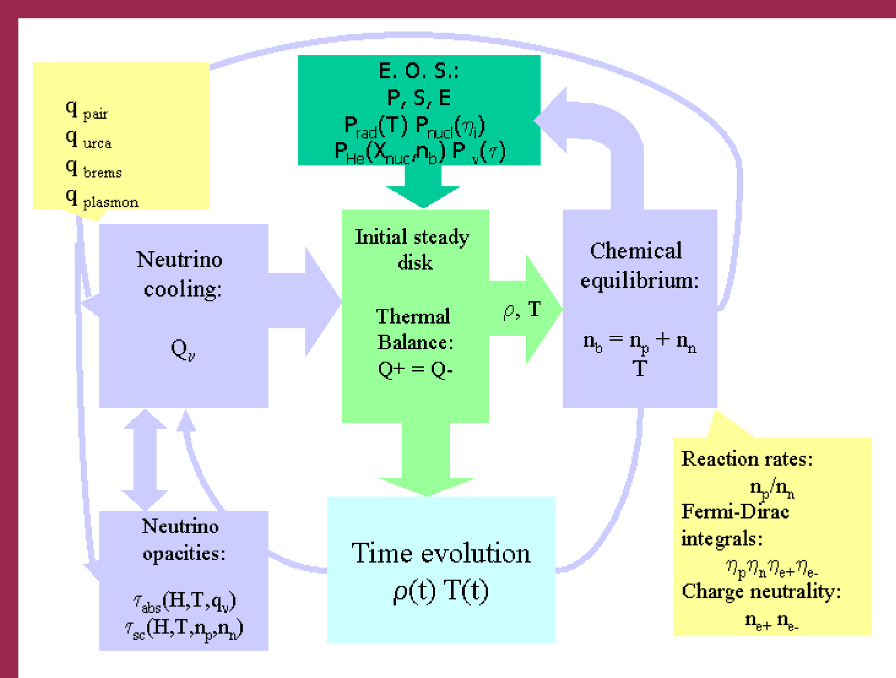
- Electron – positron capture on nucleons and β-decay

$p + e^- \rightarrow n + \nu_e$ $\quad n + e^+ \rightarrow p + \nu_e$ $\quad n \rightarrow p + e^- + \nu_e$

Thermal emission

- Annihilation of e^+e^- pairs: $e^+ + e^- \rightarrow \nu_i + \nu_i$
- Bremsstrahlung: $n + n \rightarrow n + n + \nu_i + \nu_i$
- Plasmon decay due to the interaction with electron gas:

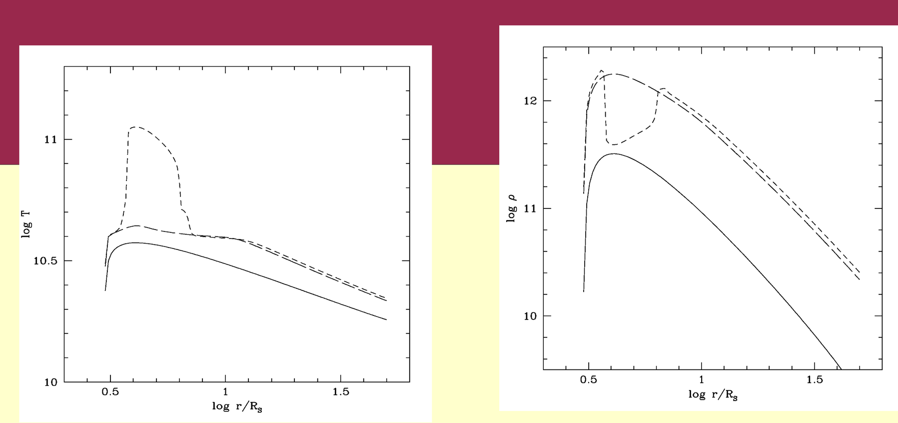
Calculation scheme



Global (several tens of R_{schw}) structure: the viscous alpha heating is balanced by the cooling due to advection, neutrino emission, photodisintegration of helium, and radiation. The EOS results are tabularized for a large range of ρ and T, and the information on composition is used to determine the photodisintegration cooling. The evolution of the torus is calculated in a viscous timescale, and the code uses Multiprocessor Communication Interface.

Disk instability for extremely high accretion rates

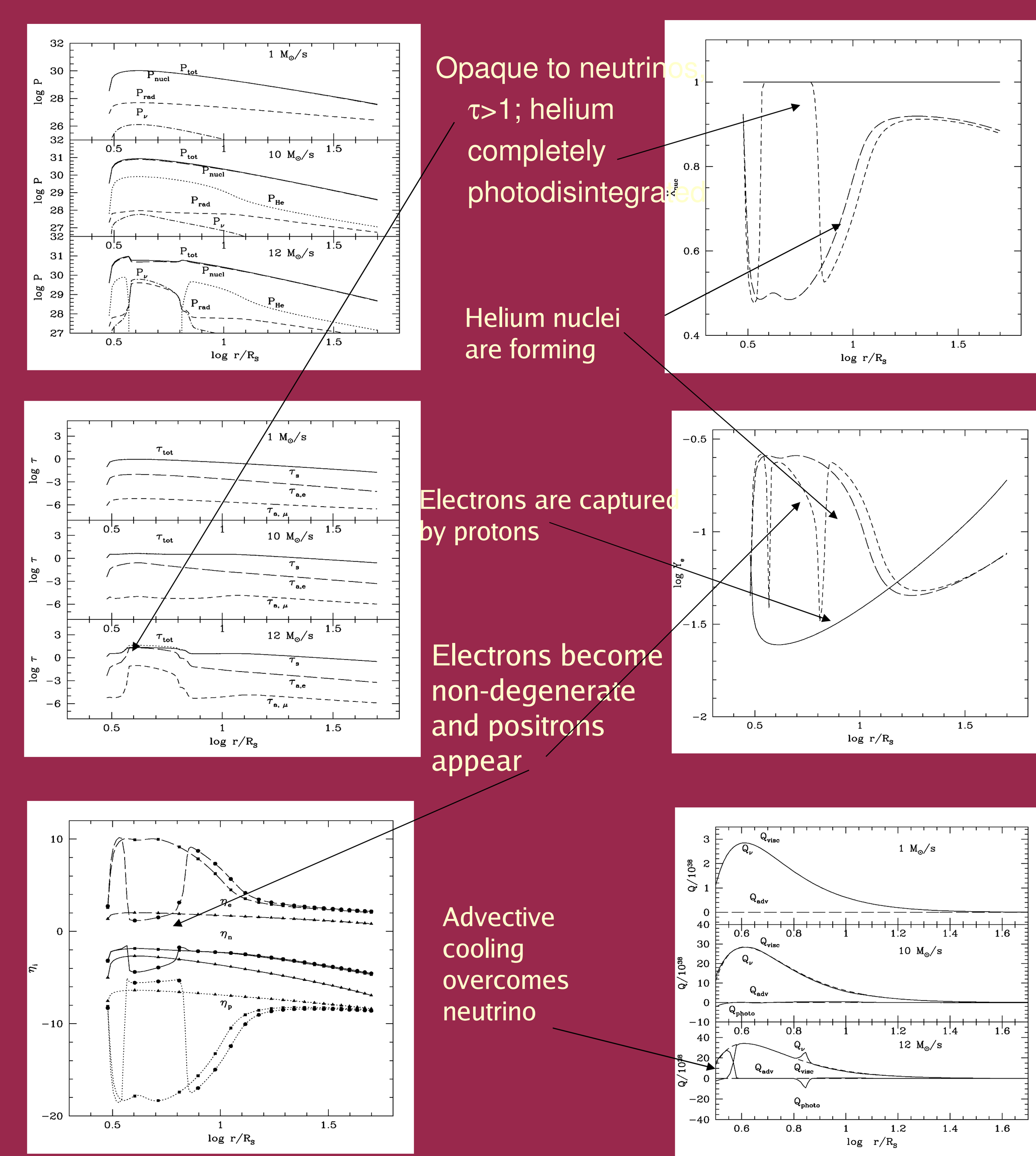
For the hottest disk model, a local peak in the density forms around 7-8 RSchw, while below that radius the density decreases. Between 3.5 and 7 Rschw, the plasma becomes much hotter and less dense than outside of this region. This means that the macroscopic state of the system is different here due to an abrupt change in the heat capacity. The helium pressure is now vanishingly small due to the complete photodisintegration, and the nuclear pressure is slightly decreased due to the composition change: smaller number density of neutrons and larger number density of protons. The substantial contribution to the pressure is given by the neutrinos (large optical depths) and radiation pressure (increased number of electron-positron pairs). The total pressure becomes locally correlated with temperature and anticorrelated with density, thus consituting an unstable phase.



Radial profiles of temperature and density in the torus, for the accretion rates of 1, 10 and 12 M_{Sun}/s.

Time evolution: for small accretion rate the disk evolves smoothly, the density, temperature and neutrino luminosity decline exponentially with time. For largest initial accretion rates, the instabilty causes first a flickering in the neutrino luminosity and then the disk breaks.

Steady-state structure results



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