template - personal notes

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Contents

I Stellar evolution remnant

Mass prescriptions

- WD : $< 8M_\odot$
- NS : $8 - 20M_\odot$
- BH : not well constrained?

Natal kicks

- BH : not well constrained
- NS : Maxwellian, $\sigma \sim 270\mathrm{km\,s^{-1}}$? (see Hobbs et al. (2005))

II Neutron stars

$M \sim 1.4M_\odot$, $R \sim 10$km.
Highest mass observed : $2.14^{+0.10}_{-0.09}M_\odot$ (Cromartie et al., 2019)
In general, softer equation of state yields more compact stars, small radii, relatively small max mass. See Özel & Freire (2016) for a review.
absolute upper limit to the NS spin frequency - mass shedding limit - constraint on the EOS about 1000Hz
the highest observed spin rate : 716Hz (Hessels et al., 2006)

1 FORMATION

Progenitor : Type II SNe ($> 8M_\odot$). Neutrinos play a crucial role in the collapse. Interior of proto-NS lose energy rapidly by neutrino emission.
Gravitational binding energy released during collapse is about

$$\frac{3}{5}\frac{GM^2}{R} \sim 0.1Mc^2 \sim 10^{53}\text{erg} \tag{1}$$

Kinetic energy of the expanding SN remnant is about $\sim 10^{51}$erg; nearly all the energy is carried off by neutrinos and anti-neutrinos.

2 STATE OF MATTER

Typical Fermi energies of a NS are of the order MeV $\sim 10^{10}\mathrm{K}$, therefore the temperature becomes only important when it is very high; otherwise $T = 0$ (cold matter) is a good approximation.
There is no 'pure' neutron stars[1] - an actual NS contains a mixture of n, p, and e.
β-decay and inverse β-decay :

$$n \rightarrow p + e + \bar{\nu}_e \tag{2}$$
$$p + e \rightarrow n + \nu_e \tag{3}$$

Fermi energy level rises more quickly for electrons, so the neutron decay (2) becomes energetically less favorable around a critical density $\sim 10^7\mathrm{g\,cm^{-3}}$ (Pauli blocking) and as the density more electrons are captured into

[1] Free neutron lifetime is about 15 minutes (Gonzalez et al., 2021).

neutrons: beta equilibrium. This results in the formation of Coulomb crystals of progressively more neutron-rich nuclei [2].

At matter densities a few times the n_0, the nucleon Fermi energies becomes so large that it is energetically favorable to transform into heavier baryons such as hyperons via electroweak interactions.

III Astrophysical black holes

1 HOW TO OBSERVE

- X-ray binaries
  LMXB :
  HMXB :
- Microlensing e.g. OGLE
- LIGO-VIRGO observations

2 MASS

stellar mass BHs : stellar evolution from massive MS star with $8 - 20M_\odot$; IMBH : $10^2 - 10^4 M_\odot$, extremely rare, GW190521; SMBH : $\sim 10^8 M_\odot$;

References

Cromartie H. T., et al., 2019, Nature Astronomy, 4, 72

Gonzalez F. M., et al., 2021, Physical Review Letters, 127, 162501

Hessels J. W. T., Ransom S. M., Stairs I. H., Freire P. C. C., Kaspi V. M., Camilo F., 2006, Science, 311, 1901

Hobbs G., Lorimer D. R., Lyne A. G., Kramer M., 2005, Monthly Notices of the Royal Astronomical Society, 360, 974

Özel F., Freire P., 2016, Annual Review of Astronomy and Astrophysics, 54, 401

[2] Laboratory nuclear matter has nearly equal number of neutrons and protons.