PHYC 581: High Energy Astrophysics

Fall 2018

Homework Assignment #5

(Due December 7, 2018)

1- Consider a neutron star accreting from a low-mass companion at a rate $\dot{M} = 2 \times 10^{16}$ g s^{-1}. The neutron star (of mass $M = M_\odot$ and radius 10 km) has a surface magnetic field $B_0 = 2 \times 10^{12}$ G, and there is evidence that the accretion occurs via a thin disk. Over time, the neutron star's spin equilibrates to the Keplerian frequency at the magnetic radius.

(a) What is the neutron star's equilibrium spin period in this system?

(b) Suppose the accretion rate increases by 20% and remains at that value indefinitely. How long will it take for the neutron star to reach its new equilibrium spin period? (Hint: Assume the neutron star is a hard uniform sphere.)

2- We see emission lines centered at $\approx$ 550 keV and $\approx$ 450 keV, believed to arise from electron-positron annihilation in a galactic superluminal jet source. Estimate the inclination of the twin jets relative to the line-of-sight, and their speed, in order for them to produce these lines.

3- Show that X-ray bursts can only occur on neutron stars-a signature that clearly differentiates these compact objects from white dwarfs and black holes. Some useful data are:

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\begin{aligned}
\text{Persistent Luminosity} &: \quad L_0 = 2 \times 10^{37} \text{ erg s}^{-1} \\
\text{Burst Luminosity} &: \quad L = 2 \times 10^{38} \text{ erg s}^{-1} \\
\text{Inter} - \text{burst period} &: \quad \Delta t_{\text{acc}} = 3 \text{ h} \\
\text{Burst duration} &: \quad \Delta t_{\text{burst}} = 30 \text{ s} \\
\text{Nuclear energy release} &: \quad \Delta E_{\text{nuc}} = 0.007c^2 \text{ erg g}^{-1}
\end{aligned}
$$

(Hint: Compare the energy released during accretion between bursts with that liberated during the bursts themselves.)

4- As the core collapse following a supernova explosion or a gamma-ray burst, the matter density eventually reaches the point where the process of neutronization converts most of the protons and electrons into neutrons. In this problem, we will estimate the density at which electron capture begins for a simple mixture of hydrogen nuclei (protons) and degenerate electrons,

$$p^+ + e^- \to n + \nu_e \,.$$

(a) In a completely degenerate gas, the electrons are packed very tightly, with a separation between neighbors $\sim n_e^{-1/3}$, where n_e is the electron number density. Use the Heisenberg uncertainty principle to estimate the average electron velocity, assuming they may be treated nonrelativistically. (The electrons do reach relativistic energies during the collapse, but this approximation is workable for the estimate sought here.)

(b) In the spirit of approximation, we will also ignore the energy taken away by the neutrinos (which, in fact, carry away a measurable and dynamically important luminosity). Obtain an alternative expression to your answer in part (a) for the electron's velocity in terms of the rest mass energy lost during neutronization.

(c) Estimate the density ρ at which the electron capture begins.

5- High-energy observations of a superluminal active nucleus show that its X-ray flux changes significantly on a time scale of 30 seconds. Assuming these X-rays ($E \sim 10$ keV) are produced when the "soft" disk photons ($E_0 \sim 0.01$ keV) are inverse-Compton scattered by particles in the jet, how big do you estimate the X-ray region to be? What is the distance in units of the Schwarzschild radius r_S for $M = 10^7 M_\odot$? Is the variability therefore likely to be due to changes in the disk or to changes in the jet acceleration region?