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Compact Star cooling with quark-hadron continuity

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Neutron stars are high-density objects remained after a supernova explosion, in which the entire star is likened to a single atomic nucleus. Due to their high density exceeding the density of the nuclear density, it has been discussed that states and particles that do not appear in a normal nucleus can appear inside a neutron star. The realisation of superfluid states of neutrons and protons, and the appearance of quark matter and/or hyperons are considered to be possible. Such states have a significant impact on neutrino emission, the dominant cooling process in neutron stars, and appear in the thermal evolution of neutron stars. In particular, the superfluid state has a large effect on suppressing neutrino emission and has a significant impact on the thermal evolution of the neutron star. Comparison of temperature observations and cooling calculations of neutron stars allows us to constrain the internal state of the neutron star.

We have developed a model for the appearance of quark matter in a colour superconducting state in the core of a neutron star and performed cooling calculations. The colour superconducting state may have multiple pairings depending on the degree of freedom of the quark colour and flavour, we assume that the CFL(Colour-Flavour Locked) or 2SC (Two-Flavour Colour Superconducting) phases appear. We also introduced a quark-hadron continuity in which the $^3P_2$ superfluidity of neutrons in the hadronic phase on the low-density side is taken over by unpaired d-quarks in the 2SC phase on the high-density side, and we included that state (2SC+$< dd >$ phase) in the cooling calculations.

We found that the cooling curves of neutron stars with the 2SC+$< dd >$ phase pass through a higher temperature range than those with the 2SC phase, and are similar to the CFL phase. According to these results, we can conclude that the 2SC+$< dd >$ phase can be realised in neutron stars having lower observed temperatures.

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