論文の内容の要旨

Physical properties of strange-modes appearing in pulsations of very luminous stars (非常に明るい星の脈動に現れるストレンジモードの物理的性質)

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Stars keep hydrostatic equilibrium during most of their lifetimes. But many of them show some variability of the brightness in short timescales. While the causes for the variability are mass ejecting, rotation, flare, etc., pulsation is also responsible for it. Stellar pulsations are phenomena that a star repeats to expand and shrink periodically. Stellar pulsations are powerful tools to investigate the stellar interior. Simultaneously, they are thought to affect profiles of stellar structure by inducing mass loss, angular momentum transfer, etc. It had been originally known that there had been two types of pulsation modes, p (pressure) and g (gravity) modes. Their physical properties are well-understood, and the results by the nonadiabatic analyses are well-matched with those by the adiabatic analyses. In theoretical models of very luminous stars with $L/M \gtrsim 10^4 L_\odot/M_\odot$ such as massive stars, helium stars and Wolf-Rayet (WR) stars, etc., on the other hand, there exist eigenmodes which show different behaviors from p and g modes, and they have been called "strange-modes". Envelopes of very luminous stars have strong nonadiabaticy, and some of the strange-modes cannot be obtained as solutions in adiabatic analyses. Although their physical properties are puzzling, pulsationally unstable strange-modes have extremely high growth rate and might be influential on stellar evolutions.

So far analyses of strange-modes have been carried out with the frozen-in convection (FC) approximation, under which convective luminosity perturbation is neglected. In envelopes of hot massive stars, particularly, convection is not so dominant as in those of stars in the redder side of the classical instability strip. But excitation of the strange-modes takes place in convection zones, and we cannot definitely say that convection never affects the pulsations. In this study, analyses of strange-modes are carried out by adopting the time-dependent convection (TDC) theory, which deals with convection-pulsation interactions (§4). Fig.1 shows instability domains of radial pulsations. This study found that convection suppresses pulsational instability of some of the strange-modes. The excitation of such modes takes place at the Fe opacity bump, around which convection certainly contributes to energy transport. But it is confirmed that the strange-mode instability certainly exists

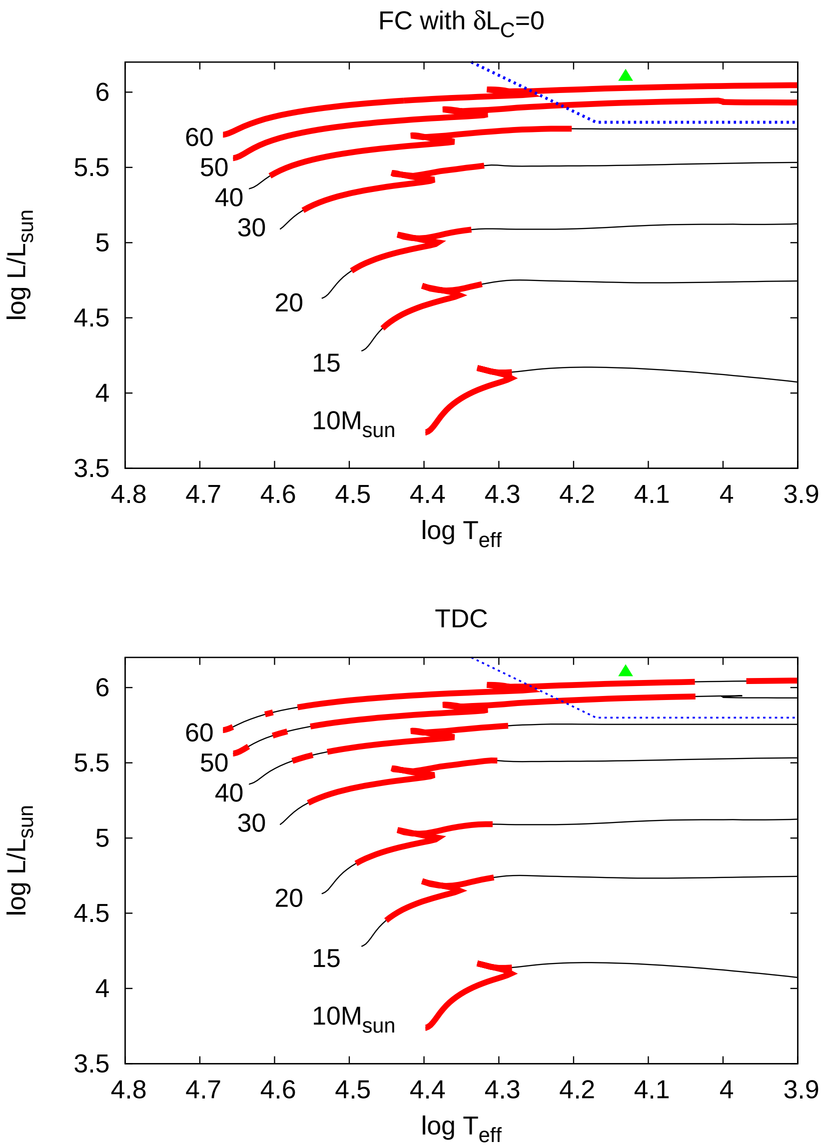

Figure 1: Pulsational instability domains in the HR diagram. The top and the bottom panels are obtained by FC and TDC, respectively. The black lines are evolutionary tracks of $10 - 60M_{\odot}$ stars. The red colored parts indicate evolutionary stages having pulsational instability. The blue dashed line is the HD limit, and the green filled triangle is HD 50064, a candidate for a strange-mode pulsator.

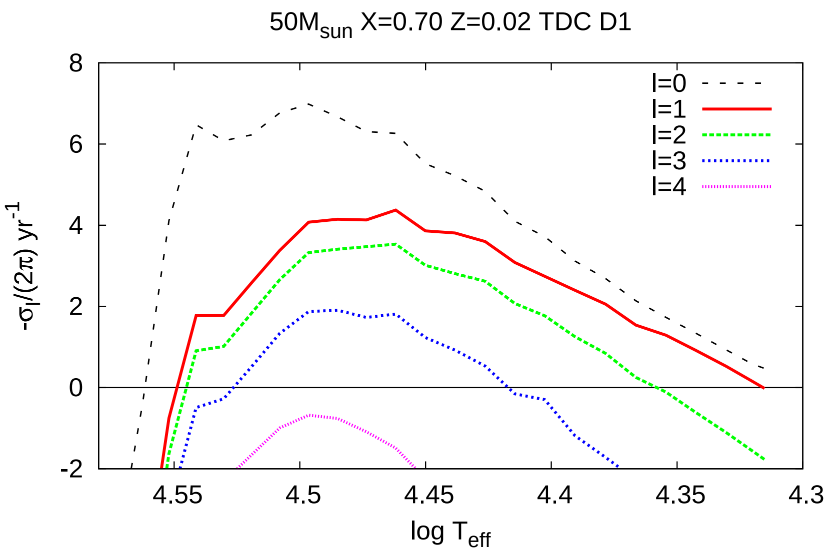

Figure 2: Growth rate of the strange-mode for $l = 0-4$ in the main-sequence stage for $50M_\odot$ by TDC. The positive value of $-\sigma_I/2\pi$ means pulsational instability.

even if convective effects are included. Especially, the extent of the instability appearing around the Humphreys-Davidson (HD) limit does not vary between FC and TDC treatments. The corresponding mode is excited around the He opacity bump, around which the layer is convectively unstable, but the convective luminosity is negligible. Then, this mode is free from convective effects. This instability might be responsible for the lack of observed stars over the HD limit. Actually, luminous blue variables are located around the HD limit. They experience sporadic eruptions repetitively, and then are thought to evolve toward WR stars. Although there is still no established mechanism for the eruptions, the strange-mode instability could be the trigger. In addition, a recent observation found a luminous B star HD 50064 to change its mass loss rate on a timescale of the 57 day period of photometric and spectroscopic variation, and the period seems to correspond to a strange-mode.

Nonradial pulsations are also analyzed in the main-sequence stage (§6). Nonradial modes have an additional parameter l, which indicates the number of node lines on the stellar surface. In the low l cases, the mode amplitude is confined to the outer layer including the Fe bump. As the l increases, however, waves become propagate in the radiative zone below the Fe bump convective zone. That is, the amplitude leaks to this zone and the mode comes to suffer from radiative damping. The instability becomes weaker with increasing l, and finally disappears with $l = 4$ (Fig.2). That is, the radial pulsation ($l = 0$) is most responsible for the instability.

This study also investigates the physical origin of strange-modes (§5). In fact, there are two types of strange-modes, one with and without adiabatic counterparts. The type having adiabatic counterparts appears in the main-sequence stage, while the other type is dominant in the post main-sequence stage. The type with adiabatic counterparts has the corresponding solutions in the adiabatic analysis. This type is excited by the classical κ-mechanism like the ordinary modes. According to the WKB approximation based on the adiabatic approximation, a propagative cavity is formed around the Fe opacity bump due to small density gradient. In envelopes of very luminous star, radiation pressure is dominant around the Fe bump, and strongly pushes the upper layers. Then, the upper

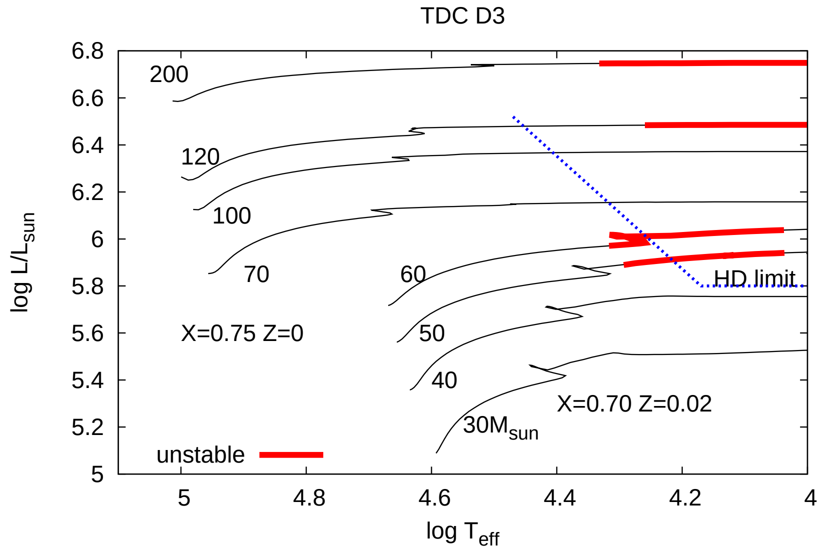

Figure 3: The black lines are evolutionary tracks for Population I ($X = 0.70$, $Z = 0.02$) stars with $M = 30 - 60M_\odot$, and for Population III ($X = 0.75$, $Z = 0$) stars with $M = 70 - 200_\odot$ in the HR diagram. The red lines indicate the range of instability of the strange-mode D3, the type which cannot be explained by the adiabatic analysis.

layers need relatively high density to obtain enough gravity competing with the radiation pressure, and the outward decline in density is suppressed to maintain the hydrostatic equilibrium. In this situation, waves are trapped in the propagative cavity, and the mode amplitude is confined there. This leads to strong excitation of the κ-mechanism at the Fe bump.

On the other hand, the second type, the strange-modes without adiabatic counterparts are not excited by the κ-mechanism. Instead, dominance of radiation pressure is important. The excitation of this type of strange-mode is subject to the scheme for the diffusive process of photons. In case that thermal energy flux is extremely strong, heat capacity of matter is relatively small. When some perturbation takes place and one region is compressed, the opacity increases due to the higher density, and the region receive stronger radiation than its surroundings. But since it cannot save the extra received thermal energy generated by the perturbation due to the poor heat capacity, temperature (radiation pressure) gradient is produced so that the energy can flow to the other zones. This study demonstrates that this type of instability is suppressed and needs higher luminosity in the zero-metallicity case, where radiation pressure is weaker than the Population I case due to lack of heavy element opacity (Fig.3). While this type of instability takes place for $\gtrsim 50M_\odot$ in the Population I case, it does for $\gtrsim 120M_\odot$ in the Population III case. With the zero-metallicity, cooling process through line emission of heavy elements lacks during the star formation stage. Due to this, core of protostars has high temperature and hence high accretion rate. Then, we can expect that very massive stars were formed in the early Universe. Particularly, the pair-instability supernova (PISN) is proposed in the mass range of $130 - 300M_\odot$. Its existence is controversial since it produces peculiar chemical composition. The instability of the strange-mode could be influential on the evolutionary scenario toward PISN.