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恒星内部对流超射

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恒星内部存在着对流运动, 对流运动起到输运物质和能量的作用, 会对恒星结构和演化产生重要的影响. 由于对流的输运作用, 物质和能量会从对流不稳定区向对流稳定区扩散, 此现象被称为对流超射. 对流超射是当前恒星物理最不确定和最困难因素之一.

描述恒星内部对流超射的经典方法是非局地混合长理论. 但是, 这种理论是唯象理论, 建立在不牢固的基础上, 学者对此类唯象理论有多方面的批评和不满. 最近, 日震学研究否定了非局地混合长理论框架下的对流超射图景, 同时表明, 目前只有使用湍流模型描述对流超射才能产生符合日震学的结果, 这为研究恒星内部的对流超射指明了方向.

在本论文的综述部分中, 首先介绍了恒星内部对流超射的经典处理方法及其优缺点, 然后详细介绍了被日震学研究推荐的恒星湍流模型, 包括模型的物理基础、推导过程和优缺点. 本论文的研究工作部分包含了湍流模型的理论分析和实际应用方面, 并建立了一个对流超射混合的新模型.

在恒星湍流模型的理论分析方面, 通过合理的假设和简化, 得到了湍流模型的近似解和其在超射区中的渐近解, 了解了超射区的结构. 在很大的模型参数范围内, 得到的近似解和渐近解都与数值计算结果符合得很好. 通过理论分析, 还得到与模型参数无关的一个重要结果, 即超射区的传热区大约为对流边界之外的1 HK范围内(HK为湍流动能标高).

在恒星湍流模型的应用方面, 有3个计算实例. 在太阳模型的应用中, 发现湍流模型描述下的对流超射区的温度梯度轮廓与日震学反演结果很好地符合, 使用扩散型对流超射混合和合适的参数可以同时大幅改善太阳模型的Li丰度、声速轮廓和密度轮廓. 在星团小质量恒星中使用与太阳模型相同的参数来描述对流壳层底部的超射混合, 可以使星团(研究了Hyades、Praesepe、NGC6633、NGC752、NGC3680 和M67这6个星团)的Li丰度对有效温度的关系与观测符合, 并估算出此类恒星的Li丰度损耗e-fold时标为1 Gyr. 在双星HY Vir 模型的应用研究中, 本文利用该双星系统的观测性质研究了扩散型对流超射混合的合适强度, 然后研究了使用湍流模型和扩散型对流超射混合的情况下的恒星内部结构特点, 发现前两项应用得到的参数同样适用于HY Vir系统对流核超射, 使HY Vir的恒星参数与观测符合, 并发现和解释了扩散型对流超射混合使超射区e-fold长度随时间变大.

通过上述研究提供的线索, 本论文在流体力学方程组的基础上建立了湍流化学组分通量的湍动对流模型, 解出了其局地模型的对流/超射混合的扩散系数. 扩散系数表达式在对流不稳定区与超射区有着不同的近似行为, 揭示了湍动对流运动在超射区中的性质与对流不稳定区不同: 在超射区中, 浮力阻做负功, 流体在其平衡位置附近运动, 混合特征尺度比对流不稳定区里的情况小得多. 该结果揭示了超射区中的扩散系数很小, 混合效率很低, 在多方面与经典模型不同, 而与日震学和数值模拟相符合. 最后, 将这个新的超射混合模型应用于恒星模型中, 利用一些观测特性定标了模型参数的大小, 并解释其物理含义.

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Convective Overshoot in Stellar Interior

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In stellar interiors, the turbulent thermal convection transports matters and energy, and dominates the structure and evolution of stars. The convective overshoot, which results from the non-local convective transport from the convection zone to the radiative zone, is one of the most uncertain and difficult factors in stellar physics at present.

The classical method for studying the convective overshoot is the non-local mixing-length theory (NMLT). However, the NMLT bases on phenomenological assumptions, and leads to contradictions, thus the NMLT was criticized in literature. At present, the helioseismic studies have shown that the NMLT cannot satisfy the helioseismic requirements, and have pointed out that only the turbulent convection models (TCMs) can be accepted.

In the first part of this thesis, models and derivations of both the NMLT and the TCM were introduced. In the second part, i.e., the work part, the studies on the TCM (theoretical analysis and applications), and the development of a new model of the convective overshoot mixing were described in detail.

In the work of theoretical analysis on the TCM, the approximate solution and the asymptotic solution were obtained based on some assumptions. The structure of the overshoot region was discussed. In a large space of the free parameters, the approximate/asymptotic solutions are in good agreement with the numerical results. We found an important result that the scale of the overshoot region in which the thermal energy transport is effective is 1 HK (HK is the scale height of turbulence kinetic energy), which does not depend on the free parameters of the TCM.

We applied the TCM and a simple overshoot mixing model in three cases. In the solar case, it was found that the temperature gradient in the overshoot region is in agreement with the helioseismic requirements, and the profiles of the solar lithium abundance, sound speed, and density of the solar models are also improved. In the low-mass stars of open clusters Hyades, Praesepe, NGC6633, NGC752, NGC3680, and M67, using the model and parameter same to the solar case to deal with the convective envelope overshoot mixing, the lithium abundances on the surface of the stellar models were consistent with the observations. In the case of the binary HY Vir, the same model and parameter also make the radii and effective temperatures of HY Vir stars with convective cores be consistent with the observations.

Based on the implications of the above results, we found that the simple overshoot mixing model may need to be improved significantly. Motivated by those implications, we established a new model of the overshoot mixing based on the fluid dynamic equations, and worked out the diffusion coefficient of convective mixing. The diffusion coefficient shows different behaviors in convection zone and overshoot region. In the overshoot region, the buoyancy does negative works on flows, thus the fluid flows around the equilibrium location, which leads to a small scale and low efficiency of overshoot mixing. The physical properties are significantly different from the classical NMLT, and consistent with the helioseismic studies and numerical simulations. The new model was tested in stellar evolution, and its parameter was calibrated.