Heating of protoplanetary disks by shock waves produced by giant planets: Analysis of entropy changes

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Understanding the thermal structure of protoplanetary disks is an essential task in clarifying the origin of the compositional distribution of planetary systems. Recent disk temperature calculations based on magnetohydrodynamics indicate that the interior of the disk is cooler than previously thought and that solids can retain large amounts of water ice even near the current Earth orbit. If such a low-temperature disk is realistic, our understanding of the formation of rocky planets in the solar system, including the Earth, may have to undergo a major revision. On the other hand, there is a possibility that the conventional disk temperature models have overlooked an important disk heating mechanism.

In this study, we focus on disk heating by shock waves produced by giant planets as one of such heating mechanisms. The possibility that Jupiter was born early in the primordial solar nebula has recently attracted attention as one of the most promising interpretations of the isotopic dichotomy of meteorites. When such a giant planet exists in the disk, a spiral disk density wave called a spiral is excited by the planetary gravity and propagates to the far side of the planet. When this spiral becomes a shock wave as it propagates, it causes irreversible heating of the disk gas (shock wave heating). Recent hydrodynamic simulations have shown that shock wave heating can contribute to the temperature rise of the disk within a few au of the central star. However, this previous study focuses on the disk temperature, which is the final output of the simulation, and not on the shock wave heating itself. Since the disk temperature depends on other heating processes and assumptions about radiative cooling, it is not possible to model the effect of shock wave heating in a more general situation from this result.

In this study, we aim to clarify the effect of planetary shock wave heating on an arbitrary disk and make a new attempt to extract and quantify the shock wave heating itself from fluid simulations. Specifically, we calculated the distribution of spirals created by giant planets using two-dimensional hydrodynamic calculations and measured the amount of heating, or entropy increase, that occurs when the spirals become shockwaves. We focused on the entropy increase instead of the temperature or density change to exclude the short-term and periodic temperature change caused by the adiabatic expansion and compression of the density wave and to extract only the irreversible heating that contributes to the long-term temperature increase.

As a result, we found that the amount of shock wave heating in each orbit of the disk follows a simple power law of the distance from the planetary orbit and the planetary mass. In addition, the entropy analysis revealed how far away from the planet each of the multiple spirals excited in the disk becomes a shock wave. Comparing the shock wave heating calculated directly from the measured entropy increase with that calculated indirectly from the areal density jump at the same point using the Rankine-Hugoniot relation, it was found that the former tended to have less dependence on the resolution of the fluid simulation. This suggests that the calculation of shock wave heating based on entropy analysis is less susceptible to numerical effects.

The empirical equation for the shock wave heating due to planetary density waves derived in this study allows us to investigate the effect of shock wave heating on the disk temperature distribution without performing multi-dimensional fluid calculations. In particular, by applying our empirical equation to simulations of the intra-disk evolution of dust, which controls the radiative cooling efficiency of the disk, it will be possible to clarify how the solid and disk temperatures evolve simultaneously in the protosolar nebula with Jupiter.

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