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Strong parameter hierarchy in the interstellar phosphorus chemical network

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Abstract-

Phosphorus-bearing molecules are fundamental for life on Earth, yet their astrochemical origins remain poorly understood. Their formation in the interstellar medium has been challenging to elucidate due to limited spectroscopic detections and the reliance on theoretical models that depend on numerous kinetic parameters whose values are very uncertain. Multi-parameter models often suffer from “sloppiness”, where many parameter combinations exhibit negligible influence on model outcomes, while a few dominate system behavior. In this study, we introduce the Fisher Information Spectral Reduction (FISR) algorithm, a novel and computationally efficient method to reduce the complexity of such sloppy models. Our approach exposes the strong parameter hierarchy governing these systems by identifying and eliminating parameters associated with insensitive directions in the parameter space. Applying this methodology to the phosphorus astrochemistry network, we reduce the number of reaction rate coefficients from 14 to 3, pinpointing the key reactions and kinetic parameters responsible for forming PO and PN, the main phosphorus-bearing molecules typically detected in interstellar space. The simplified model retains its predictive accuracy, offering deeper insights into the mechanisms driving phosphorus chemistry in the interstellar medium. This methodology is applicable to multi-parameter models of any kind and, specifically in astrochemistry, facilitates the development of simpler, more realistic and interpretable models to effectively guide targeted observational efforts.

Index Terms- phosphorus astrochemistry, interstellar medium, astrobiology, dynamical systems, chemical reaction networks, kinetic parameters, complexity reduction, parameter sensitivity

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