第 29 卷 第 4 期
2011 年 10 月

天 文 学 进 展
PROGRESS IN ASTRONOMY

Vol.29, No. 4
Oct., 2011

博士论文摘要选登

星系中原子和分子气体的半解析模型

富 坚*

(中国科学院 上海天文台 星系宇宙学重点实验室，上海 200030)

摘 要：星际气体是星系中重子物质的重要组成部分，其中的分子气体（主要是分子氢H_2）以及原子气体（主要是中性氢HI）对于星系中发生的各个物理过程至关重要。本文在前人的星系形成和演化的半解析模型基础上，加入了描述星系盘中分子气体和原子气体成分的物理模型，来研究分子气体和原子气体对于星系形成和演化所起的作用。我们主要使用了马普天体物理所Munich Group的L-Galaxies半解析星系形成模型，并借鉴了星系化学演化模型的方法，把半解析模型中的每一个星系盘分成了多个同心圆圈，然后在每个圈中分别追踪气体下落、分子气体和原子气体转化、恒星形成、金属增丰、超新星爆发加热冷气体等发生在星系盘上的物理过程，并且每个同心圈都是独立演化的。在我们的模型中，一个基本假设是每个时间步内气体都是以指数形式下落到星系盘上，并且直接叠加在已有的气体径向面密度轮廓之上，其中指数盘的标长$r_{\rm d}$正比于星系所在暗物质晕的维里半径$r_{\rm vir}$与旋转参量λ的乘积。我们的模型使用了两种描述分子气体形成的模型：一种是基于Krumholz等人 解析模型的结果，其中分子气体的比例与局域气体面密度以及局域气体金属丰度相关；另一种是分子气体比例与星际压强相关的模型，根据Obreschkow 等人 的近似，分子气体的比例与气体面密度以及恒星质量面密度相关。由于恒星形成过程发生在星际巨分子云之中，并且根据Leroy 等人 的观测结果，恒星形成率面密度近似正比于分子气体的面密度，因此我们在模型中使用了与分子气体面密度相关的恒星形成规律。

我们的模型基于Millennium模拟结果的合并树之上运行，给出的结果与近年来的一些近邻盘星系的恒星、中性氢、分子氢的径向面密度轮廓的观测结果基本一致（比如来自SINGS、THINGS、HERACLES、BIMA SONG 等观测项目的结果），并且能够和$Z=0$处观测所得的恒星、中性氢、分子氢的质量函数相符合。在此基础上，我们探究了星系整体分子气体、原子气体、恒星质量的比例随星系恒星质量、平均气体面密度、平均恒星面密度的变化趋势，并使用了模型中3个不能直接观测的量来解释这种与气体成分有关的标度关系，这3个量是星系晕的维里质量、星系盘的旋转参量、近期星系所吸积的冷气体的比例。

最后，我们对模型进行了一些扩展工作。第一个扩展是在盘上加入描述离子气体成分的

* **该作者博士毕业时间**：2011 年 7 月； **指导老师**：中国科学院上海天文台侯金良研究员

模型，我们利用了Gnedin 和Kravtsov 的星际气体电离–复合模型，从而得到一个与恒星远紫外辐射场有关的分子气体形成模型。这个分子气体形成模型给出的结果中，在星系盘较内侧金属丰度较高的区域中性气体面密度较低，这或许有助于解释DLA 吸收体中金属丰度和中性氢柱密度呈反相关趋势的结果。第二个扩展是引入盘上气体径向内流过程，用来解决$\Sigma_{\rm SFR} \propto \Sigma_{\rm H_2}$的恒星形成率导致星系盘内部气体消耗过快而外部气体消耗过慢的问题。第三个扩展是在已有的基于Millennium II输出结果之上的半解析模型中加入描述研究分子气体和原子气体的物理过程。由于Millennium II的模拟解析度比Millennium模拟高125倍，因此可以研究高红移星系以及低质量矮星系中的气体成分。目前模型结果能很好地符合红移0处的观测，包括红移 $z = 0$处的恒星、中性气体、分子气体的质量函数等。但在高红移时与观测还有偏差，这可能由观测和模型两方面的原因引起的。但与之前模型结果相比，新的模型结果有明显的改进，尤其是恒星质量–气体金属丰度关系随红移演化的结果。

The Semi-Analytic Models of Neutral and Molecular Gas in Galaxies

FU Jian

(Key Laboratory for Research in Galaxies and Cosmology, Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China)

Abstract: Interstellar gas is important baryonic components in galaxies, in which molecular gas (mainly molecular hydrogen H_2) and neutral gas (mainly atomic hydrogen HI) have great effect on the physical processes in each galaxy. In this thesis, we develop physical models about neutral gas and molecular gas in galaxy disks based on previous semi-analytic models (SAMs) of galaxy formation, and we use the model to study the role of neutral and molecular gas in galaxy formation and evolution. Our model is a modified version of the SAMs named L-Galaxies by Munich Group in Max-Planck Institute for Astrophysics. According to the methods used in the models of galaxy chemical evolution, we divide each galaxy disk into a series of concentric rings in SAMs. Then we trace the physical processes in each ring on galaxy disks, such as gas infall, conversion of atomic gas to molecular gas, star formation, metal enrichment, supernova reheating etc, and the evolution in each ring is independent. In our model, we assume that the surface density profile of infalling gas is exponential in each time step, and the newly infalling gas is directly superposed on the gas radial profile already existing on the disk. The scale radius $r_{\rm d}$ is proportional to the virial radius of the halo times its spin parameter λ. We adopt two kinds of prescriptions for molecular gas formation

processes in our models: one is based on the analytic models by Krumholz et al., in which the molecular gas fraction is a function of local gas surface density and local gas metallicity. The other one is a prescription where the H_2 fraction is determined by the pressure of interstellar medium, in which the molecular gas fraction is related to gas surface density and stellar mass surface density according to the approximation by Obreschkow et al. Since star formation processes happen in giant molecular clouds, and the observational results from Leroy et al. show that star formation rate surface density is approximately proportional to molecular gas surface density, we use H_2 surface density related star formation law in our models based on the molecular gas formation prescriptions.

We run the models on the merger trees of Millennium Simulation outputs. Our models give the results of radial surface density profiles of star, molecular gas and neutral gas which can fit the recent observations from nearby disk galaxies (e.g. the results from SINGS, THINGS, HERACLES, BIMA SONG and some other observation programmes). And our results can also fit the mass functions of star, neutral gas and molecular gas at $z = 0$. Based on these results, we study the global properties for the mass ratios of molecular gas, neutral gas and star vary as a function of global scale parameters, including stellar mass, mean stellar surface density, mean gas surface density. We elucidate the trends in terms of three variables which cannot be directly observed. They are the virial mass of the dark matter halo, the spin parameter of the galaxy disk and the fraction of recent accreted gas.

In the last section, we extend our models. The first work is to include the model of ionized gas in galaxy disks. We use the ionization-recombination model of interstellar gas by Gnedin & Kravtsov and get a gas molecular fraction prescription related to stellar far ultraviolet fields. Based on such kind of prescription, our model predicts that the inner regions of galaxy disks with high gas metallicity tend to have low neutral gas surface density, which may help to explain the anti-correlation between gas metallicity and HI column density in the observations of DLA absorbers. The second work is to include the process of radial gas inflow on galaxy disks, which can solve the problem of too fast gas consumption in inner disks and too slow gas consumption in outer disks when $\Sigma_{\rm SFR} \propto \Sigma_{\rm H_2}$ is adopted as the star formation law. The third work is to include the models of neutral gas and molecular gas in the previous SAMs based on Millennium II outputs. The resolution of Millennium II Simulation is 125 times higher than Millennium Simulation, so the model can help to study the gas components in galaxies at high redshift or in low mass dwarf galaxies. In our current model, the results can fit the observations at$z = 0$ quite well, including the mass functions of star, neutral gas and molecular gas at $z = 0$ and some other properties. But the model results have some difference to the observations at high redshift. This may be caused by problems both in the model recipes and in the observations at high redshift. Comparing to the previous model results, the new model has some obvious improvements, especially on the redshift evolution for the relation between stellar mass and gas metallicity.

....
....