

星系中分子气体物理性质的观测研究

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为了研究亮红外星系中分子气体的物理性质, 本论文给出了一个小样本近邻亮红外星系初步的观测结果、一个高红移星系 IRAS F10214+4724 的详细研究以及一个近邻亮红外星系 ARP 302 的高分辨率研究. 另外, 对 Perseus 星系团中存在的分子气体给出了高分辨的观测, 并研究其气体的运动学状态.

对一个小样本的亮红外星系, 得到了 CO ($J=3\rightarrow 2$) 的成图结果, 揭示其气体分布都集中在星系中心或者是并合星系的中心及其星系核的重叠区域. 对于其中的一个源 NGC 3256, 给出了其 CO ($J=3\rightarrow 2$)、CO ($J=4\rightarrow 3$) 和 CO ($J=7\rightarrow 6$) 的观测结果, 揭示其 CO 谱线能量分布的峰值在 CO ($J=5\rightarrow 4$) 与 CO ($J=6\rightarrow 5$) 之间. 通过辐射转移模型拟合多条 CO 谱线跃迁的观测流量, 限制星系中气体的物理条件: 对 $T_{\text{kin}}=40\sim 45$ K, 对应的气体密度约为 $10^{3.7}\sim 10^{4.1}$ cm^{-3} . 近邻亮红外星系 NGC 3256 与宇宙早期的亚毫米波星系 (SMGs) 具有同样的气体激发条件; 观测结果支持这样的观点: 近邻亮红外星系与 SMG 可能是同一类星系, 只是处于宇宙不同时期.

对红移为 2.286 的亮红外星系 IRAS F10214+4724 探测到了 CI ($^3P_2 \rightarrow ^3P_1$)、CO ($J=3\rightarrow 2$)、CO ($J=4\rightarrow 3$)、CO ($J=6\rightarrow 5$) 和 CO ($J=7\rightarrow 6$) 谱线跃迁以及 3 mm 和 1 mm 波段的尘埃连续谱发射. IRAS F10214+4724 也成为至今为止中性碳的两条精细结构线都探测到的第 3 个河外星系. 星系能够沿着东西方向被 CI ($^3P_2 \rightarrow ^3P_1$) 谱线观测很好地分辨, 沿东西方向的速度梯度也能很好地探测到. 由 CI 谱线强度比可以得出 CI 的激发温度为 42^{+12}_9 K. 中性碳的激发条件、CO 谱线的多条跃迁以及尘埃连续谱发射共同将气体的物理性质限制在: 气体密度 $n(\text{H}_2)=10^{3.6}\sim 10^{4.0}$ cm^{-3} 和气体温度 $T_{\text{kin}}=45\sim 80$ K, 这与近邻的星暴星系的激发条件类似. 静止波长为 360 μm 的尘埃发射的形状与谱线发射区域相比致密, 这支持了以前的发现, 即远红外流量来自离 AGN 区域更近的区域.

给出早期的并和星系 ARP 302 中北边星系 ARP 302N 的高分辨 CO ($J=2\rightarrow 1$) 观测的结果, 揭示了星系中分子气体延展的空间分布. 在这个系统中, 分子气体的分布很不对称: 有两个稠密气体区域分布在星系中心的上下两侧, 另外有一个弱的稠密气体区域在离中心偏北 8 kpc 的地方. 分子气体云的分布与 Spitzer 24 μm 中红外连续谱发射所示踪的热尘埃的分布是一致的. 对谱线强度比的激发条件分析表明: 对于整个星系, 其分子气体的密度较低, 小于 10^3 cm^{-3} . 利用尘埃模型来拟合星系的连续谱发射, 给出了尘埃温度 $T_{\text{d}}=26\sim 36$ K 和尘埃质量 $M_{\text{dust}}=2.0\times 10^8\sim 3.6\times 10^8 M_{\odot}$. 3.6 cm 射电连续谱、Spitzer 8 μm 和 24 μm 中红外数据以及 CO ($J=2\rightarrow 1$) 的高分辨观测结果之间的一致性说明了在 ARP 302N 星系中存在不对称的恒星形成活动.

对 Perseus 星系团中心 cD 星系 Perseus A (简称 Per A) 中心区域半径 ~ 10 kpc 的范围用 CO ($J=2\rightarrow 1$) 谱线在 ~ 1 kpc 分辨率下对其分子气体进行成像观测. 已知 Per A 拥有 $\sim 1.3\times 10^{10} M_{\odot}$

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的分子气体, 这些气体以前被认为是从并合星系中捕获或是由富气星系中冲压剥离, 又或是从 X 射线冷却流吸积而来. 本文第 1 次发现分子气体聚集在 3 个径向纤维状分子云, 其长度从 1.1~2.4 kpc 不等; 并且所有的分子云都分布在东西方向, 从星系中心到外径 ~ 8 kpc 处. 东边和西边外部的纤维状分子云, 在更小的半径处存在更大的蓝移速度, 而更内部的西边的纤维状分子云具有与星系系统速度相似的速度. 所有分子云都没有轨道运动的迹象, 所以不太可能从富气星系中捕获. 相反, 我们可以用在 Per A 引力势中自由下落的假设来重现两个外部的纤维状分子云所观测到的速度结构, 这暗示着分子云来自 X 射线冷却流. 确实, 所有的 3 个纤维状分子云都处于由 Per A 的射电喷流所造成的两个主要 X 射线空腔内, 这也暗示着分子云处于一个相对不被喷流所影响的区域, 而在这个区域冷却流才可以起作用. 估计在两个外部纤维状分子云的质量沉积率大约为 $76 M_{\odot} \cdot \text{yr}^{-1}$. 这个数值的冷却流能够为 Per A 的活动星系核提供一个相对连续的分子气体储备.

An Observational Study on Physical Properties of the Molecular Gas in External Galaxies

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To study the physical properties of the molecular gas in luminous infrared galaxies (LIRGs), this thesis presents the preliminary results of a small local sample, a case study on a distant LIRG IRAS F10214+4724 at $z=2.286$ and another case study on a local LIRG ARP 302. The molecular gas in Perseus A, the cD galaxy in the center of the Perseus Cluster, is presented in high angular resolution observation to study the gas distribution and its kinematics.

A small sample of 5 LIRGs was observed and the CO ($J=3 \rightarrow 2$) mapping results reveal the gas distribution concentrated in the galactic centers or the centers of mergers and their overlapping regions. For NGC 3256, the maps in the CO ($J=3 \rightarrow 2$), CO ($J=4 \rightarrow 3$) and CO ($J=7 \rightarrow 6$) transitions are obtained. Together with the measurements in the lower transitions from literatures, the peak of the spectral energy distribution (SED) of CO line was found between CO ($J=5 \rightarrow 4$) and CO ($J=6 \rightarrow 5$). With the radiation transfer model and the CO ladder, the gas density is constrained to $n(\text{H}_2)=10^{3.7} \sim 10^{4.1} \text{ cm}^{-3}$ for a kinematic temperature $T_{\text{kin}}=40 \sim 45 \text{ K}$ adopted from the literature. Local LIRG NGC 3256 shows the similar excitation conditions as the submillimeter galaxies (SMGs) in the early universe, further supporting the view that the SMGs are the same type of the local LIRGs, but only at the early epoch.

The CI ($^3P_2 \rightarrow ^3P_1$), CO ($J=3 \rightarrow 2$), CO ($J=4 \rightarrow 3$), CO ($J=6 \rightarrow 5$) and CO ($J=7 \rightarrow 6$) transitions as well as the dust continuum at 3 mm and 1 mm were detected towards the distant LIRG IRAS F10214+4724 at $z=2.286$. IRAS F10214+4724 now belongs to a sample of only 3 extragalactic sources at any redshift where both of the carbon fine structure lines have been detected. The source is spatially resolved by our CI ($^3P_2 \rightarrow ^3P_1$) observation and we detect a velocity gradient along the east-west direction. The CI line ratio allows us to derive a carbon excitation temperature of 42_{-9}^{+12} K . The carbon excitation in conjunction

with the CO ladder and the dust continuum constrains the gas density to $n(\text{H}_2)=10^{3.6}\sim 10^{4.0}$ cm^{-3} and the kinematic temperature to $T_{\text{kin}}=45\sim 80$ K, similar to the excitation conditions found in nearby starburst galaxies. The rest-frame 360 μm dust continuum morphology is more compact than the line emitting region. This supports previous findings that the far infrared (FIR) luminosity arises from regions closer to the AGN.

High angular resolution observation in CO ($J=2\rightarrow 1$) was carried out towards ARP 302N, the northern galaxy of the early merging system ARP 302, revealing the extended spatial distribution of the molecular gas in ARP 302N. The molecular gas was shown as a very asymmetric distribution with two strong concentrations on both sides of the center together with a weaker one offset by about 8 kpc to the north. The molecular gas distribution is also found to be consistent with that from the hot dust as traced by the 24 μm continuum emission observed by Spitzer. For an observed line ratio of CO ($J=2\rightarrow 1/1\rightarrow 0$), excitation analysis suggests that the gas density is low, less than 10^3 cm^{-3} , over the entire galaxy. By fitting the SED of ARP 302N in the FIR band, we obtain a dust temperature of $T_{\text{d}}=26\sim 36$ K and a dust mass of $M_{\text{dust}}=2.0\sim 3.6\times 10^8 M_{\odot}$. The good spatial correspondence among the 3.6 cm radio continuum emission, the Spitzer 8 & 24 μm data and the high resolution CO ($J=2\rightarrow 1$) observation from the SMA (submillimeter array) shows that there are asymmetrical star forming activities in ARP 302N.

The molecular gas in Perseus A (Per A) has been imaged in CO ($J=2\rightarrow 1$) at a spatial resolution of ~ 1 kpc over a central region of radius ~ 10 kpc. Per A is known to contain $\sim 1.3\times 10^{10} M_{\odot}$ of molecular gas, which has been proposed to be captured from mergers or ram-pressure stripping of gas-rich galaxies, or accreted from an X-ray cooling flow. For the first time, the molecular gas detected in our images can be seen to be concentrated in three radial filaments with lengths ranging from 1.1 kpc to 2.4 kpc. These all lie in the east-west directions, spanning from the center of the galaxy to radii of ~ 8 kpc. The eastern and outer western filaments exhibit larger blueshifted velocities with decreasing radii, while the inner western filament spans the systemic velocity of the galaxy. The molecular gas shows no signature of orbital motion, and therefore is unlikely to have been captured from gas-rich galaxies. Instead, we are able to reproduce the observed kinematics of the two outer filaments as free-fall in the gravitational potential of Per A, suggesting that they originate from an X-ray cooling flow. Indeed, all three filaments lie between two prominent X-ray cavities carved out by radio jets from Per A, suggesting that they are located in a relatively undisturbed region where a cooling flow is able to operate. The inferred mass-deposition rate into the two outer filaments alone is roughly $76 M_{\odot}\cdot\text{yr}^{-1}$. This cooling flow can provide a nearly continuous supply of molecular gas to fuel the active nucleus in Per A.