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Molecular Absorption Lines in Galaxies

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Abstract. Molecular absorption lines have become an important tool in studying the astrochemistry of the dense and cold interstellar medium in both our own Galaxy and high redshift systems. The sensitivity is to first order only dependent on the observed continuum flux. Apart from a few nearby galaxies, molecular absorption lines have been used to study the molecular ISM in 4 galaxies at redshifts 0.25-0.89. A large number of molecular species and transitions have been observed, allowing a detailed comparison with molecular gas in our own Galaxy. Planned instruments, such as ALMA, will allow studies of a larger number of molecular absorption line systems.

1. Introduction

The presence of molecules in the interstellar medium (ISM) has been known for almost 70 years. The very first detection of the molecular ISM was done through observations of narrow absorption lines at optical wavelengths, seen towards bright stars in our own Milky Way galaxy (Merrill 1934). Through extensive detective work it was soon established that these lines were due to molecules in interstellar space (Russell 1935; Swings & Rosenfeld 1937). Today more than 120 molecular species are known to exist in interstellar space. Many of these molecules are complex, containing as many as 13 atoms. These complex species are interesting from an astrochemical point of view, but in order to specify the basic physical and chemical parameters of the molecular gas a smaller set of diagnostic molecules suffice. Knowledge of the physical and chemical properties of the molecular gas allows us to gain an understanding of star formation processes. In the Milky Way these parameters are known through observation of rotational transitions of diagnostic molecular species, radiating at millimeter and sub-millimeter wavelengths.

In external galaxies, however, it becomes increasingly difficult to get a detailed picture of the molecular gas and its physical and chemical properties. This is mainly due to the low covering factor of molecular gas, given the angular resolution provided by existing telescopes, resulting in a low observed signal strength. In addition, some molecules require very high densities and temperatures to be excited and produce observable emission. This situation becomes even more severe for very distant galaxies, where even the best interferometer systems fail to resolve the molecular gas distribution. It is therefore not surprising that the very first detection of molecular gas in external galaxies was done using absorption lines rather than emission lines. With the Parkes 64m telescope, Whiteoak & Gardner (1973) detected OH in absorption towards the starburst galaxy NGC253. This was followed by detection of additional OH absorption in NGC4945 (Whiteoak & Gardner 1975) in the LMC (Whiteoak &

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Gardner 1976b), and H_2CO in Centaurus A (Gardner & Whiteoak 1976) and in the LMC (Whiteoak & Gardner 1976a).

The first molecule to be observed in emission in external galaxies was CO (Rickards et al. 1975; Solomon & de Zafra 1975). Since then CO emission has become the standard probe for molecular gas in external galaxies, providing us with pertinent information about the distribution of the molecular gas, its kinematics and the total gas mass. Observation of several different rotational transitions gives a handle on the temperature and density of the molecular component, but little information on the chemical properties of the gas. To achieve the latter, it is necessary to observe additional molecular species, preferably in several different rotational transitions. The sensitivity of today's instruments usually limits this to a few simple molecules in the central regions of the most nearby galaxies.

2. Molecular Absorption Lines

The use of molecular absorption lines allows observation of many more molecular species than that possible using the corresponding emission lines. The sensitivity is, to first order, only limited by the observed strength of the background continuum source. The drawback is that the extent of the background source is very limited and only a very small volume of the molecular gas is probed. When using quasars (QSOs) as background sources, the angular extent can be as small as a few tens of μarcsec. Another, and more limiting constraint, is the fact that suitable background sources are scarce at millimeter and sub-millimeter wavelengths. Nevertheless, for the most distant objects, molecular absorption lines are the only means available for probing the details of the physical and chemical conditions of the molecular gas.

Molecular absorption occurs whenever the line of sight to a background quasar passes through a sufficiently dense molecular cloud. The molecular gas in nearby galaxies is strongly concentrated to the central regions, making the likelihood for absorption largest whenever the line of sight passes close to the center of an intervening galaxy. Molecular absorption in intervening galaxies is therefore likely to be associated with gravitational lensing.

For optically thin *emission* the observed property is the emission integrated over velocity, $I_{\rm CO}$, where: $I_{\rm CO} = \int T_{\rm a}\, dv \;\propto\; N_{\rm tot}\, T^{-1}\, e^{-E_{\rm u}/kT}\, (e^{{\rm h}\nu/{\rm k}T} - 1)\, [J(T) - J(T_{\rm bg})]$. $N_{\rm tot}$ is the total column density of a given molecular species, $E_{\rm u}$ is the upper energy level of a transition with $\Delta E = h\nu$, $T_{\rm bg}$ is the local temperature of the Cosmic Microwave Background Radiation (CMBR) and $J(T) = (h\nu/k)(e^{h\nu/kT} - 1)^{-1}$. When $T \rightarrow T_{\rm bg}$ the signal disappears. For molecular *absorption* the observable is the velocity integrated opacity $I_{\tau_\nu} \propto N_{\rm tot}\, T^{-1}\, \mu_0^2\, (1 - e^{-h\nu/kT}) \approx (h\nu/k)\, N_{\rm tot}\, \mu_0^2\, T^{-2}$, where $N_{\rm tot}$ is again the total column density of a given molecular species and μ_0 is the permanent dipole moment of the molecule[9].

[9]This expression is strictly speaking only true for linear molecules but represents a reasonable approximation for non-linear molecules as well.

The dependence on $(\mu_0/T)^2$ means that the observability of molecular absorption lines increases with the strength of the permanent electric dipole moment and decreasing gas temperature - a situation which to a large extent is the inverse to that of molecular emission. If multiple gas components are present in the line of sight, with equal column densities but characterized by different excitation temperatures, absorption will be most sensitive to the gas component with the lowest temperature. The dependence of the opacity on the permanent dipole moments also means that molecules much less abundant than CO can be as easily detectable. For instance, HCO^+ has an abundance which is of the order 5×10^{-4} that of CO, yet it is as easy, or easier, to detect in absorption as CO. This is illustrated in Fig. 1, where the observed opacity of the CO(1-0) and HCO^+(2-1) transitions at $z = 0.25$ are compared. In this particular case, the HCO^+ line has a higher opacity than the CO line.

Table 1. Properties of molecular absorption line systems.

Source	z_a (abs)	z_e (emission)	N_{CO} cm^{-2}	N_{H_2} cm^{-2}	N_{HI} cm^{-2}	A_V	N_{HI}/N_{H_2}
Cen A	0.00184	0.0018	1.0×10^{16}	2.0×10^{20}	1×10^{20}	50	0.5
PKS1413+357	0.24671	0.247	2.3×10^{16}	4.6×10^{20}	1.3×10^{21}	2.0	2.8
B3 1504+377A	0.67335	0.673	6.0×10^{16}	1.2×10^{21}	2.4×10^{21}	5.0	2.0
B3 1504+377B	0.67150	0.673	2.6×10^{16}	5.2×10^{20}	$< 7 \times 10^{20}$	<2	<1.4
B 0218+357	0.68466	0.94	2.0×10^{19}	4.0×10^{23}	4.0×10^{20}	850	1×10^{-3}
PKS1830-211A	0.88582	2.507	2.0×10^{18}	4.0×10^{22}	5.0×10^{20}	100	1×10^{-2}
PKS1830-211B	0.88489	2.507	$1.0 \times 10^{16\ (e)}$	2.0×10^{20}	1.0×10^{21}	1.8	5.0
PKS1830-211C	0.19267	2.507	$< 6 \times 10^{15}$	$< 1 \times 10^{20}$	2.5×10^{20}	<0.2	>2.5

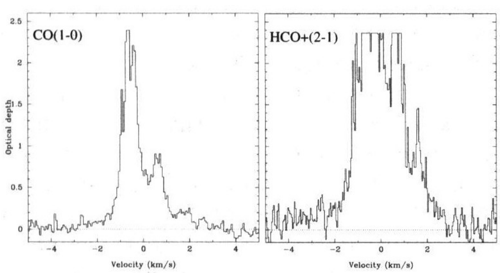

Figure 1. The observed opacity for the CO(1-0) and HCO^+(2-1) transitions seen at $z = 0.25$ towards PKS1413+135. The opacity of the HCO^+(2-1) line is larger than that of the CO(1-0) line despite of an abundance which is $10^{-3} - 10^{-4}$ that of CO.

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3. Known Molecular Absorption Line Systems

Local absorption systems Molecular absorption line studies is a relatively new field, both for our own Galaxy and for external galaxies. The small angular extent of QSOs at millimeter wavelengths (tens of μarcsec) means that for local molecular clouds, the observed signal is dominated by emission from areas within the telescope beam not covered by the continuum source. It is only with interferometers operating at millimeter wavelengths that it is possible to effectively utilize molecular absorption lines within our own Galaxy. This technique has been used by Lucas & Liszt in an extended study of the diffuse molecular component in the Milky Way (cf. Liszt & Lucas 2002; Lucas & Liszt 2002 and references therein).

Apart from the early observations of OH and H_2CO absorption in nearby galaxies, it is only Cen A and the radio galaxy 3C390 that allows absorption line measurements. Both these systems posses a relatively strong flat spectrum AGN. Cen A in particular shows a rich assortment of absorption lines, with several components spread over more than 60 km s^{-1} (cf. Eckart et al. 1990; Israel et al. 1991; Wiklind & Combes 1997a).

High redshift absorption systems There are four known molecular absorption line systems at higher redshift: z=0.25-0.89. These are listed in Table 1 together with data for the low redshift absorption system seen toward the radio core of Cen A. For the high redshift systems, a total of 22 different molecules have been detected, in 32 different transitions: CO, CN, CS, OH, (SO), (LiH), HCO^+, HOC^+, HCN, HNC, N_2H^+, H_2O, H_2CO, HC_3N, C_2H, C_3H_2, $C^{13}O$, $C^{18}O$, $H^{13}CO$, $H^{13}CN$ and $HC^{18}O^+$. Molecules in parenthesis are tentative detections. Some of these molecules, OH, C_2H, C_3H_2 and HC_3N, are detected at cm wavelengths (cf. Menten, Carilli & Reid 1999; Kanekar et al. 2003). As can be seen from Table 1, the inferred H_2 column densities varies by $\sim 10^3$. The isotopic species are only detectable towards the systems with the highest column densities.

Two of the four known molecular absorption line systems are situated within the host galaxy to the 'background' continuum source: PKS1413+135 (Wiklind & Combes 1994) and B3 1504+377 (Wiklind & Combes 1996b). The latter exhibits two absorption line systems with similar redshifts, z=0.67150 and 0.67335. The separation in rest-frame velocity is 330 km s^{-1}. The two absorption line systems with the highest column densities occur in galaxies which are truly intervening and each acts as a gravitational lens to the background source: B0218+357 and PKS1830-211. In these two systems several isotopic species are detected as well as the main isotopic molecules, showing that the main lines are saturated and optically thick (Combes & Wiklind 1995; Combes & Wiklind 1996; Wiklind & Combes 1996a, 1997b, 1998). Nevertheless, the absorption lines do not reach the zero level, showing that only part of the lensed images are covered by obscuring molecular gas.

Abundance ratios Since most molecules have been observed in two or more transitions, it is possible to determine the excitation temperature and, with the assumption of weak thermal equilibrium, the total column density (cf. Wiklind & Combes 1997b). The H_2 column density remains unknown, but abundance ratios between the observed molecular species do not differ from that of corresponding molecular gas in the Milky Way (cf. Wiklind 2003). The abundance of HCO^+ is elevated relative to the models of diffuse gas, in the same manner as found for Galactic gas when derived through molecular absorption lines (cf. Wiklind & Combes 1997b; Lucas & Liszt 1996).

4. Special Issues

Rare transitions Apart from the more common molecular species, such as CO, HCN, HCO^+, H_2CO, N_2H^+, etc, redshifted molecular absorption lines can also be used to study transitions that have frequencies which normally fall outside transparent atmospheric windows. Such as the ground transition of water vapor, H_2O, LiH and molecular oxygen, O_2. The ground transition of H_2O was first detected at z= 0.678 (Combes & Wiklind 1995), and a tentative detection of LiH was done in the same system (Combes & Wiklind 1998). Molecular oxygen, however, remains undetected (Combes & Wiklind 1995; Combes, Wiklind & Nakai 1997). In fact, the upper limit to the O_2 line achieved through ground based molecular absorption lines is at par with the latest upper limits to the O_2 abundance measured with dedicated satellites (Pagani et al. 2003). Both sets of observations suggests that the abundance of O_2 in dark clouds is $\sim 10^{-5}$ the predicted abundance from chemical models. Among several different possible explanations to this (cf. Wiklind 2003), the inclusion of grain-reactions into the chemical models appears promising (Roberts & Herbst 2003).

Future Challenges The main difficulty with using molecular absorption lines in studying the detailed composition of the molecular ISM in external galaxies is that these systems are rare; about 100 times less frequent than damped Lyman-α systems. The molecular gas is less extended than other components of the ISM, with a relatively small volume covering factor. Several surveys of potential absorption line systems have so far not found any (see Curran et al. these proceedings and references therein). With planned new instruments, such as ALMA, and a significant increase in the instantaneous wavelength coverage of the receivers, the number of molecular absorption line systems is expected to grow.

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