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CO-to-H_2 Conversion Factor in Galaxies

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Abstract

A general method and formulae to derive the CO-to-H_2 conversion factor in galaxies as a function of the metallicity are presented based on an analysis of the observed data for the conversion factor obtained for nearby spiral and dwarf irregular galaxies. From the CO data for eight galaxies we obtained the following formula, which gives the conversion factor (X^*) as a function of metallicity:

$$\log X^* = -1.0\,(12 + \log \mathrm{O/H}) + A,$$

where $X^* = N_{\mathrm{H}_2}/I_{\mathrm{CO}} \times 10^{-20}$ $\mathrm{H_2/(K\ km\ s^{-1})}$ and A is a constant. Since the metallicity is dependent on the luminosity of galaxies, we derived a correlation between the conversion factor and the absolute magnitude of galaxies. We also investigated dependence of the conversion factor on the distance from the center of individual galaxies. We also present a formula to calculate X^* as a function of the radius in a galaxy.

Key words: Galaxies: abundance — Galaxies: ISM — Galaxy: general — ISM: abundance — ISM: molecules

1. Introduction

The determination of the mass of molecular-hydrogen gas in galaxies is fundamental for an understanding of the interstellar physics and star formation in galaxies. The principal method for this uses a conversion from the intensity (or luminosity) of the $^{12}\mathrm{CO}(J = 1\text{–}0)$ molecular line emission (I_{CO} or L_{CO}) into the column density (or mass) of H_2 molecules (N_{H_2} or M_{H_2}).

The conversion factor, $X (= N_{\mathrm{H}_2}/I_{\mathrm{CO}} = M_{\mathrm{H}_2}/L_{\mathrm{CO}}) = X^* \times 10^{20}$ $\mathrm{H_2/(K\ km\ s^{-1})}$, has been derived for molecular clouds in the solar vicinity based on the assumption of a virial equilibrium of individual clouds, using the large-velocity-gradient approximation for the formation of the CO line (Young, Scoville 1984; Sanders et al. 1984). This method has also been used to derive the conversion factor in nearby spiral and dwarf irregular galaxies, such as M31, M33, and the Magellanic Clouds, where individual clouds can be resolved (Wilson, Scoville 1990, 1992; Sofue et al. 1994a; Rubio et al. 1993a,b). A more global value in our Galaxy has been derived by using a correlation between the distribution of the γ-ray intensity, which is assumed to be proportional to the column mass of hydrogen atoms and molecules, and that of the CO intensity along the galactic plane (Bloemen et al. 1986; Grenier et al. 1996). A correlation between the CO intensity and the optical extinction (A_V), which is assumed to be correlated with the column mass of hydrogen, has also been used, and has been applied to well-studied galaxies, such as M51 (Nakai, Kuno 1995).

Bloemen et al. (1986) and Solomon et al. (1987) have summarized the X values so far obtained by various authors based on various methods. The conversion factor obtained in the solar vicinity from the virial-mass method appears to be scattered around $X^* \sim 2$–3 within a factor of 1.5 (see subsection 2.1). The X values derived from the virial method are consistent within a factor of two with that obtained from independent estimates, such as by the γ-ray method (Bloemen et al. 1986; Strong et al. 1988; Grenier et al. 1996), and the A_V (extinction) method (Solomon et al. 1987). The consistency between the virial method (Adler et al. 1992) and the A_V method (Nakai, Kuno 1995) has been more clearly demonstrated within the metal-rich galaxy M51.

Thus, the X values from various methods are rather consistent within a factor of two in so far as the same objects and regions are concerned. On the contrary, even though we have compared values derived from the same (virial) method, the X values are largely scattered among galaxies over an order of magnitude from the galactic value of $X^* \sim 2$–3 to such high values as for low-metallicity galaxies, like the Large and Small Magellanic Clouds, with $X^* > 15$ (Rubio et al. 1993a, b; Cohen et al. 1988). Hence, one would suppose that there is a dependence of the conversion factor X on the metallicity, at least for galaxies of sub-solar metal abundance (Cohen et al. 1988; Maloney, Black 1988; Ohta et al. 1993). For metal-richer galaxies, since the CO line is generally optically thicker, the X value has been supposed to be insensitive to the metal abundance (Maloney, Black 1988). On the other hand, a careful theoretical calculation of the conversion factor for realistic interstellar molecular clouds, which are not optically thin for the CO line, based on the LVG (large-velocity-gradient) model, has shown that the X value decreases with increasing metallicity (Sakamoto 1996). Recently, Nakai and Kuno (1995) showed that the Sc galaxy M51, whose metallicity is much higher than the solar neighborhood average, exhibits a significantly lower conversion factor of $X^* \sim 1.1$; a similar value was obtained by Adler et al. (1992). This suggests that the X value is dependent on the metallicity, even in such higher metallicity galaxies. The conversion factor should also be dependent on other physical conditions, such as the interstellar UV fields, which vary from galaxy to galaxy. In this paper, however, we try to derive an empirical relation between the conversion factor and metallicity, which are both observable within a reasonable scatter for some galaxies. We will propose possible formulae to derive X for individual galaxies as a function of the metallicity, which might, of course, implicitly contain a dependence on other factors.

Since the X values have been found to be scattered within a factor of two among the various methods, we adopt here those obtained by using the virial-mass method in most cases. Even in this method, different authors use different numerical factors in the virial formula etc., and different definitions of the cloud radius. We therefore homogenized the parameters as much as possible, even though it was sometimes not easy in practice, and had to use the values as they appeared in the literature after possible corrections. However, these may not significantly affect the result, since the present purpose is to examine the metallicity dependence of the X value over an order of magnitude among galaxies, while the ambiguity caused by the adopted parameters would be within a factor of two.

2. Observational Data

Although many observational efforts have been made to derive the conversion factor (X), no clear trend with other observable properties has emerged. This is partly because X has been derived from data taken with various methods. It is therefore important to adopt the same method to derive the conversion factor. In this paper we confine ourselves in principle to the values of X that are directly derived from the CO line intensity (I_{CO} or L_{CO}) and the virial mass of the clouds. For a virial-mass calculation, a density profile of $\rho \propto r^{-1}$ was assumed; the virial mass is written as (MacLaren et al. 1988)

$$M_{\mathrm{vir}} = 190\, R \Delta V^2, \tag{1}$$

where R is the radius of the cloud and ΔV is the full width at half-maximum intensity of the CO emission. The contribution of helium to the mean molecular weight is explicitly taken into account by assuming the solar-abundance ratio. The conversion factors X derived for individual galaxies are given in table 1. Column (1) gives the galaxy identification; columns (2) and (3) give the conversion factor X and the references for the sources.

We comment that the conversion factor would be weakly dependent on the virial mass as $X \propto M_{\mathrm{vir}}^{-0.25}$, as derived from the cloud size–velocity dispersion relation, so that the virial method would infer overestimated X values for small mass clouds (Maloney 1990). However, the results presented in this paper, where we infer a metallicity dependence of the X factor over an oder of magnitude among various galaxies, are not significantly affected by such slight overestimates for low-mass clouds.

The CO abundance should be proportional to the carbon abundance in the interstellar medium because oxygen is more abundant than carbon in any galaxy. Although it is rather difficult to measure the carbon abundance of the inter-cloud medium using ground-based spectroscopy, one can indirectly estimate the carbon abundance of the ISM from the oxygen abundance in the H II regions, if the relative carbon-to-oxygen ratio is known. In addition, the amount of CO molecules is proportional to the oxygen abundance if the relative ratio of carbon-to-oxygen is a function of the oxygen abundance. Dufour (1986) suggested that C/O varies like O/H in irregular galaxies. Moreover, the solar ratio of carbon to oxygen is consistent with the C/O vs O/H relation for irregular galaxies. One can therefore assume that the relative C/O ratio is proportional to the oxygen abundance in all disk galaxies. The oxygen abundance, $12 + \log\,(\mathrm{O/H})$, and the references are given in columns (4) and (5) of table 1, respectively. In the followings we discuss the methods and values of the conversion factor for each galaxy.

2.1. *The Milky Way Galaxy*

There have been two major methods used to derive the conversion factor; the current values are summarized in Bloemen et al. (1986). A comparison of the CO intensities of individual molecular clouds with their virial masses, which are estimated from the velocity dispersion and spatial extent, has been used to derive the averaged conversion factors for giant molecular clouds in the solar neighborhood of the galactic disk ($X^* = 3.6$: Sanders et al. 1984; Young, Scoville 1984; $X^* = 3.0$: Solomon et al. 1987).

An alternative approach is to compare the distributions of the galactic γ-ray intensity and the CO emission;

Table 1. Conversion factor and metallicity of disk galaxies.

Galaxy (1)	X^* (2)	Ref. (3)	12+log O/H (4)	Ref. (5)
M31 (molecular cloud)	1.8 ± 0.5	1	9.01 ± 0.09	16
M31 (dark cloud)	31	2	9.14 ± 0.09	16
M31 (dark cloud)	35.6	3	9.13 ± 0.09	16
M31 (molecular cloud)	3.1 ± 1.5	4	9.01 ± 0.09	16
M31 disk average	2.4 ± 1.5	1,4	9.01 ± 0.1	16
IC 10	6.6 ± 2.2	5	8.31 ± 0.20	17
NGC 55	60	6	8.34 ± 0.07	18
M33	4.1 ± 2.2	7	8.70 ± 0.06	19
M33 (NGC 604)	4.2 ± 1.3	8	8.51 ± 0.03	19
M33 (NGC 595)	6.7 ± 2.2	8	8.44 ± 0.09	19
M33 average	5.0 ± 1.5	7,8	8.5 ± 0.1	19
SMC	60:	9	8.04 ± 0.06	20
SMC	15.9 ± 5.6	10	8.04 ± 0.06	20
SMC (complexes)	30.9 ± 19.9	10	8.04 ± 0.06	20
SMC average	23 ± 10	10	8.04 ± 0.06	20
LMC	16.8 ± 8.4	11	8.37 ± 0.12	20
NGC 6822	6.6 ± 3.9	12	8.16 ± 0.06	17
Milky Way				
$(3.5 \le r < 4.5)$	2.09 ± 0.97	13	9.23 ± 0.04	21
$(4.5 \le r < 5.5)$	2.14 ± 0.90	13	9.16 ± 0.04	21
$(5.5 \le r < 6.5)$	2.26 ± 0.96	13	9.09 ± 0.04	21
$(6.5 \le r < 7.5)$	2.54 ± 1.09	13	9.02 ± 0.04	21
$(7.5 \le r < 8.5)$	2.69 ± 1.15	13	8.90 ± 0.04	21
$(8.5 \le r < 9.5)$	2.98 ± 1.62	13	8.88 ± 0.04	21
$(9.5 \le r < 10.5)$	3.74 ± 2.39	13	8.81 ± 0.04	21
Milky Way average near Sun	2.8 ± 1.6	13	8.9 ± 0.04	21
M51				
$(0.0 \le r < 2.2)$	0.88 ± 0.11	14	9.41 ± 0.12	16
$(2.2 \le r < 4.5)$	1.41 ± 0.72	14	9.32 ± 0.12	16
$(4.5 \le r < 6.7)$	2.08 ± 1.17	14	9.23 ± 0.12	16
M51 whole galaxy	1.1 ± 0.1	14	9.3 ± 0.1	16
M51				
$(0.0 \le r < 2.0)$	1.08 ± 0.49	15	9.35 ± 0.12	16
$(2.0 \le r < 4.0)$	1.46 ± 0.76	15	9.28 ± 0.12	16
$(4.0 \le r < 6.0)$	2.36 ± 1.83	15	9.22 ± 0.12	16

Note to table — Column (1): Galaxy ID. For the Milky Way Galaxy and M51, r indicates the distance from galaxy centre in kpc. A distance $D = 7.7$ Mpc is assumed for M51. Column (2): Conversion factor X in units of $10^{20}\mathrm{cm}^{-2}(\mathrm{K\ km\ s}^{-1})^{-1}$. Column (3): References to column (2). Column (4): Abundance of oxygen. Column (5): References to column (4).

References: 1) Vogel et al. (1987); 2) Sofue, Yoshida (1993); 3) Allen, Lequeux (1993); 4) Sofue et al. (1994b); 5) Wilson, Reid (1991); 6) Dettmar, Heithausen (1989); 7) Wilson, Scoville (1990); 8) Wilson, Scoville (1992); 9) Rubio et al. (1991); 10) Rubio et al. (1993a,b); 11) Cohen et al. (1988); 12) Wilson (1994); 13): Solomon et al. (1987); 14) Nakai, Kuno (1994) 15) Adler et al. (1992); 16) Zaritsky et al. (1994): we used a fitted line to the data for each galaxy in this reference; 17) Lequeux et al. (1979); 18) Vigroux et al. (1987); 19) Vílchez et al. (1988); 20) Dufour et al. (1982); 21) Shaver et al. (1983)

a value of $X^* = 2.8 \pm 0.3$ has been derived (Bloemen et al. 1986; Strong et al. 1988). Recently, EGRET observations have yielded a smaller value of a factor of 1.7 than by that obtained COBE observations, namely $X^* \sim 1.5$ for the whole Galaxy (Grenier et al. 1996). They also reported a larger value (2.5 ± 0.9) in the outer arm than the local value (2.2 ± 0.6), which suggests a radial gradient of X in the Galaxy. The γ-ray values are systematically smaller than those from the virial-mass method by a factor of 1.5.

We now consider a possible correlation between the virial-method conversion factor and the metallicity in the Milky Way based on the fact that the Galaxy has a well-established metal gradient (Shaver et al. 1983). We used and reanalyzed the CO data of molecular clouds presented by Solomon et al. (1987), who gave the CO luminosity, velocity dispersion, virial masses, and distances for a large number of galactic molecular clouds. We recalculated the conversion factors for individual clouds, and divided the data into those falling into annulus zones of the galacto-centric distance at every 1 kpc, and calculated the averaged X values in each zone. Table 1 lists the obtained values, where the Sun's position is assumed to be at $r_{\odot} = 8$ kpc. The metal abundance, as defined by 12 + log O/H, is known to be an exponentially decreasing function of r: -0.07 dex kpc^{-1} (Shaver et al. 1983). We used this relation to calculate the metal abundance at each galactocentric distance, whereby we adopted the latest abundance determination of the ISM in the solar neighborhood: $12+\log\,(\mathrm{O/H})_{\odot} = 8.90$ (Anders, Grevesse 1989). We list the calculated values in table 1.

2.2. M51

Nakai and Kuno (1995) have extensively studied the conversion factor and its radial distribution in M51 based on their high-resolution (15″) full mapping of the entire disk in the CO-line emission using the Nobeyama 45-m telescope; we adopt their latest data here. They measured the mass of $\mathrm{H_2}$ gas using the amount of interstellar extinction A_V values, as derived from a comparison of H_α and the radio continuum fluxes of the H II regions. The thus-derived conversion factor therefore gives an independent estimate of that obtained from the conventional virial method. They obtained $X^* = 1.1 \pm 0.1$ for the whole disk. They have also given X values at different radii, finding that the conversion factor increases with the distance from the nucleus. M51 is a metal-rich disk galaxy with a clearly defined abundance gradient (Zaritsky et al. 1994). Nakai and Kuno further compared the X value with those from the literature for other galaxies, and suggested the dependence of the conversion factor on the metallicity. A factor of 4.5 smaller value than the galactic value was derived for the central region by Guélin et al. (1995) by comparing mm-wave dust emission and the CO intensity.

On the other hand, based on their BIMA interferometer observations, Adler et al. (1992) derived a consistent value ($X^* \sim 1.2$) for giant clumps of several hundred pc diameters along the spiral arms, assuming the virial equilibrium formula, equation (1) (MacLaren et al. 1988). They also derived the X values at different radii, suggesting a significant radial gradient that is consistent with the result of Nakai and Kuno (1995). It is remarkable that these two independent estimates gave a nearly identical value, which strongly supports our use of the virial method to evaluate the conversion factor.

2.3. M31

This nearest Sb galaxy provides a unique opportunity to resolve out individual molecular clouds in spiral arms using mm-wave instruments. Lada et al. (1987) have identified three molecular clouds in the SW 7 kpc arm using the Nobeyama 45-m telescope at 15″ resolution. Vogel, Boulanger, and Ball (1987) mapped this region using the Owens Valley mm-wave interferometer at a resolution of 7″ (25 pc). They have given a CO intensity and virial mass for a giant molecular cloud in this region. Using their data we calculated the conversion factor to be $X^* = 1.8$. Sofue et al. (1994b) have used the Nobeyama mm-wave Array to map the densest part in CO emission (Ryden, Stark 1986) of the eastern spiral arm at a galactocentric distance of 7 kpc and a resolution of 4″. They resolved several molecular clouds, and obtained conversion factors for individual clouds by applying the virial mass estimation; they found a slightly larger value than that in our Galaxy. Thereby, no correction for the missing flux for extended components has been applied. Since both the CO luminosity and the virial mass of a cloud are similarly dependent on the cloud size, to which the missing extended flux contributes, the X value would not significantly differ from that after a correction of the extended flux is applied. We, here, recalculated the conversion factor from their data in a consistent way with the other data to obtain the values given in table 1.

The central region of M31 has no definite disk structure of gas, and exhibits a peculiar interstellar condition, such as an anomalous morphology of gas (Sofue 1994), an extremely small optical extinction and very weak CO emission (Sofue, Yoshida 1993; Sofue et al. 1994a), and/or an extremely weak starlight field (Allen, Lequeux 1993). Although some anomalously large values have been suggested by these observations (table 1), no definite value has been obtained for the central region. We, here, did not use these anomalous values in the center of M31.

2.4. M33

Wilson and Scoville (1990, 1992) mapped a number of molecular clouds in the inner 1 kpc region of M33 and its H II regions, NGC 604 (r = 1.5 kpc) and NGC 595 (r = 4.5 kpc), using the Owens Valley interferometer at a resolution 7″ (30 pc). They obtained an agreement of the virial mass for the clouds in the inner disk with the molecular mass estimated by using the galactic conversion factor, concluding that the galactic conversion factor applies to M33. Using their data we recalculated the conversion factor to be $X^* = 4.1 \pm 2.2$. They found a slightly larger X value for the clouds near to the H II regions in the outer region, where a lower metallicity has been observed (Vílchez et al. 1988). They pointed out a possible dependence of the conversion factor on the metallicity. Also, the data could be potentially used for the X gradient against r, since the galaxy is known to exhibit a steep metal-abundance gradient (Vílchez et al. 1988). However, since the observed clouds, except for NGC 595, are located in the inner 1 kpc region, and the X values are too much dispersed for a simple correlation, the present data are not suitable for examining the r variation of X

2.5. LMC

Cohen et al. (1988), based on their Colombia 1.2-m telescope observations at a resolution of 8′.8 (130 pc), obtained a velocity-width vs CO luminosity relation. They derived an X^* value of 16.8 in order for the relation be consistent with that obtained for molecular clouds in the Galaxy; hence, they did not use the virial-mass estimation. Although they also calculated the virial masses for individual clouds, they were found to be much larger than that derived from the assumed conversion factor of $X^* = 16.8$. This discrepancy may be due to the fact that the clouds were not resolved by the wide beam used for the observations, as well as the fact that the cloud complexes observed within a single beam would not be gravitationally bound. Garay et al. (1993) used the same telescope to map the 30 Doradus molecular clouds. By applying the virial-mass estimation, they derived a conversion factor as large as 38.7±10.8. Since the application of the virial theorem to such a large area (at least 130 pc scale) would give an overestimated value for the mass, we do not use their data here.

2.6. SMC

Rubio et al. (1991) used the 1.2-m telescope to map molecular clouds in the SMC. By using the same method, comparing the mass-velocity relation with that for the galactic clouds, as that used by Cohen et al. (1988), they could derive a value as large as $X^* \sim 60$. Recently, more direct data for a virial-mass estimation have been obtained by Rubio et al. (1993a,b) by using the SEST 15-m telescope at a resolution of 45″ (13.5 pc). From their data for molecular clouds and virial masses we obtained a conversion factor of $X^* = 15.93 \pm 5.57$. In this paper we adopt this value, as derived from a direct measurement of the virial masses of clouds. They also gave the virial masses and CO luminosities for larger-scale complexes, which comprises multiple clouds, for which we obtained $X^* = 30.9 \pm 19.9$. This larger conversion factor than the galactic value would be due to a smaller amount of CO in a diffuse medium which is metal dependent as well as photo-dissociated by the strong UV field, and can be present only in dense molecular clouds. Hence, the metallicity dependence of the X factor in this galaxy would implicitly include the effect of a stronger UV radiation which is also dependent on the dust, and, therefore, on the metal abundance.

2.7. IC 10 and NGC 6822

Wilson and Reid (1991) mapped three molecular clouds in the metal-poor dwarf irregular IC 10 at a resolution of 6″.6 × 7″.5 (32 × 36 pc) for a distance of 1 Mpc. They also compared the molecular masses derived by using the galactic conversion factor, which was assumed to be $X^*_{\rm Gal} = 3.0 \pm 1$, with the virial masses from the size and velocity dispersion. From their relation we obtained $X^*_{\rm IC10} = X^*_{\rm Gal}(M_{\rm vir}/M_{\rm mol})(d/1\ {\rm Mpc}) = 6.6 \pm 2.2$ for a distance to the galaxy of 1 Mpc. Wilson (1994) used the same method to derive the conversion factor in three clouds in the Magellanic-type dwarf irregular NGC 6822, and obtained $X^* < 6.6 \pm 3.9$.

2.8. NGC 55

Dettmar and Heithausen (1989) used the SEST 15-m telescope to map molecular clouds in this Magellanic irregular with a resolution of 43″.5 = 420 pc at a distance of 2 Mpc. They assumed that the cloud complex with an extent of 975 pc to be in virial equilibrium, and obtained a conversion factor as large as 60. However, since it is not trivial that such a large cloud complex is in a gravitationally bound state, but might be affected by the galactic rotation/random motion, the value would be greatly over-estimated. We therefore do not use this value in our statistics.

3. The Conversion Factor X

3.1. Metallicity Dependence among Galaxies

First of all, we tried to obtain the metallicity dependence of the typical (representative) conversion factor for individual galaxies with different metallicities. When we derived a representative X value for a galaxy for which several X values are listed, we used the following X values: We used the solar-neighborhood value, $X^* = 2.8 \pm 1.6$, for our Galaxy; an averaged value of 2.4 ± 1.5 at $R \sim$ 7–9 kpc for M31; an averaged value 5.0 ± 1.5 of all three values listed for M33; and an averaged value 23 ± 11 of the two smaller values for the SMC. For M51, we adopted the value 1.1 ± 0.1 obtained by Nakai and Kuno (1995) for the whole disk, which is close to the value ($\sim$ 1.2) of Adler et al. (1992). Figure 1 is a plot of the thus-obtained representative conversion factor for each galaxy against the oxygen abundance, $12 + \log {\rm O/H}$, at the corresponding radius. The diagram demonstrates for the first time that the conversion factor indeed depends strongly on the metallicity. A simple least-squares fit gives a coefficient of the slope of -0.8, as shown by the dotted line in figure 1. We may, here, fit the plot by a simple linear relation (slope of -1.0) between the conversion factor and the metallicity, as

$$\log X^* = -1.0\,(12 + \log {\rm O/H}) + 9.30, \qquad (2)$$

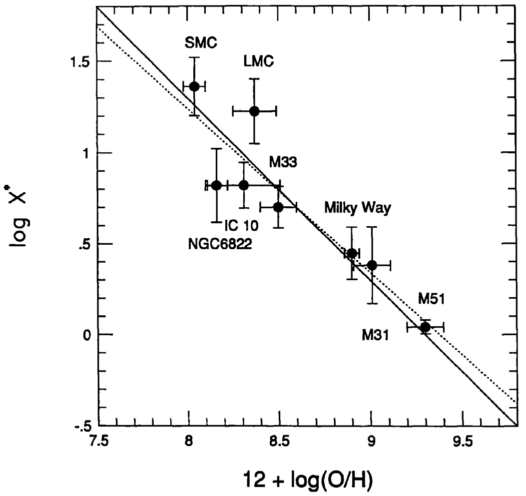

Fig. 1. Conversion factor (X^*) vs oxygen-abundance relation for eight galaxies. The different symbols indicate different galaxies. The dotted line gives a least-squares fit, and the solid line indicates the linear relation between X and the metallicity. We, here, adopt the linear relation.

or

$$X \propto Z(\mathrm{O})^{-1.0}, \tag{3}$$

as shown by the full line in the figure. Here, $Z(\mathrm{O})$ is the oxygen abundance. Our method concerning the metallicity dependence anlysis of X, by plotting log X vs 12 + log O/H [equation (2)], which was reported in a preprint, has recently been repeated by Wilson (1995), who confirmed our result using similar data for the same galaxies, except for M51.

If we assume that the C and O abundance are proportional to each other, the above equations indicate that the conversion factor is mainly controlled by $Z(\mathrm{CO})$ as

$$X \propto Z(\mathrm{CO})^{-1.0}. \tag{4}$$

On the other hand, if $Z(\mathrm{O}) \propto Z(\mathrm{C})^{1/2}$, as IUE observations have suggested (Dufour et al. 1982; Dufour 1986), and if we take into account the fact that interstellar oxygen is much richer than carbon, equation (4) may imply a weaker dependence of X on the CO abundance,

$$X \propto Z(\mathrm{CO})^{-0.5}. \tag{5}$$

The metal abundance varies with the galaxy type among spirals and irregulars in the sense that earlier galaxies have a higher abundance (Roberts, Haynes 1994). This effect only reflects the abundance-luminosity effect, and a clear correlation between the metallicity and M_B has been obtained; the plot in figure 7 of Roberts and Haynes (1994) can be fitted using

$$12 + \log \mathrm{O/H} = -0.20\ M_B + 4.86. \tag{6}$$

where M_B is the absolute blue magnitude of a galaxy. We then obtained a more convenient formula to estimate the conversion factor for a galaxy whose absolute magnitude is known:

$$\log X^* = 0.20\ M_B + 4.44. \tag{7}$$

3.2. Metallicity Dependence among Individual Regions

In figure 2 we plot all of the X values given in table 1 which we are obtained for individual regions of the galaxies in order to examine if the metallicity dependence (as mentioned above) applies to individual molecular clouds and regions. The figure shows an almost identical correlation of X on the metallicity. This result strongly suggests that, among various properties of an interstellar medium, such as the gas density and excitation temperature, the metallicity is a fundamental parameter that controls X^*. Sakamoto (1996) has examined the effect of the molecular-cloud properties on the conversion factor based on a simple model of radiative transfer and excitation of the CO line for clumpy molecular clouds, taking into account the effects of the cloud struture, gas density, kinetic temperature, and CO abundance. Since most molecular clouds in galaxies are of low density, the conversion factor was shown to be strongly dependent on the degree of photon trapping, and, therefore, on the CO abundance or metallicity. The properties of clouds other than the CO abundance have a minor effect on the conversion factor. He has shown that the X value is insensitive to the temperature of clouds if it lies in 10 – 30 K. He has thus shown that the observed characteristics in figure 2 are well reproduced by this model.

4. Discussion

4.1. Other Factors to Be Taken into Account

In the present study we assumed that the same virial-mass method applies to the Galaxy as well as to external galaxies, while the effective beam widths are different. The CO intensities for galactic clouds would contain a significant contribution from the diffuse component, which is optically thin. This fact may reduce the conversion factor in the Galaxy as well as in other galaxies (Polk et al. 1988), and would cause a systematic reduction of the X value, although it is practically impossible to apply the correction for the diffuse-component contribution in our samples. However, since the present metal dependence of the X value is over an order of magnitude on logarithmic axes, this would not significantly affect the result.

The present result demonstrates that the X factor is a function of the metallicity Z. We stress that although this result is an *empirical relation* between X and Z,

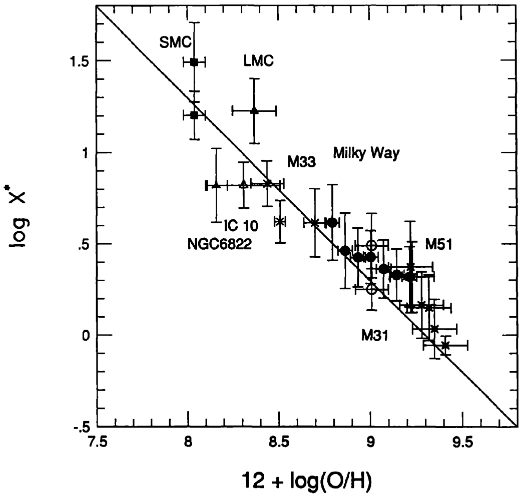

Fig. 2. Conversion factor (X^*) vs oxygen-abundance relation for individual data points in the eight galaxies. The different symbols indicate different galaxies. The solid line gives the linear relation between X and the metallicity.

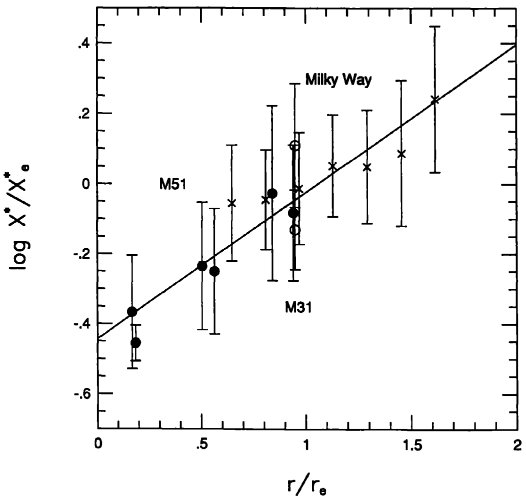

Fig. 3. Radial distribution of the conversion factor (X^*) for the Milky Way Galaxy (crosses), M31 (open circles), and M51 (filled circles). The solid line gives a least-squares fit to all of the data points.

namely, it is a plot of the data as projected on the X–Z plane, this does not mean that there is no other correlation. The relation itself might implicitly contain various physical processes, such as the photo-dissociation of H$_2$ molecules by UV photons from young stars, whose intensity on the clouds depends on the interstellar dust (metals). In fact, the UV field conditions would be different in various regions of the galaxies, which may affect the formation and dissociation process of the molecular gas. It is therefore obvious that there may exist other correlations, such as the UV intensity vs X, and the UV intensity vs Z, etc., which would be an interesting subject for the future related to molecular-gas formation under different interstellar conditions (Sofue et al. 1995; Honma et al. 1995).

4.2. Radial Gradient of the Conversion Factor

Since it is well established that the metallicity is a decreasing function of the galacto-centric distance within a galaxy (Shaver et al. 1983; Díaz 1989; Belly, Roy 1992; Zaritsky et al. 1994), the metallicity dependence of the conversion factor so far inferred would implicitly represent a radial gradient in the X value within individual galaxies. In fact, a larger X value has been obtained in the outer Galaxy (Sodroski 1991) than those for the inner Galaxy. We stress that the metal-rich galaxy M51 also exhibits a conspicuous radial gradient of the conversion factor (Nakai, Kuno 1995; Adler et al. 1992).

In figure 3, we plot the values of X^* for the Galaxy, where the radius r is normalized by the effective radius r_e, as defined by the stellar surface-brightness distribution. We also plot X^* for M51 and M31 in the same figure. Here, the effective radii of the galaxies are taken as $r_e = 6.19$ kpc for the Milky Way Galaxy (de Vaucouleurs, Pense 1978), $r_e = 7.37$ kpc for M31 (McCall 1982), and $r_e = 7.26$ kpc for M51 (Monnet et al. 1981).

The Galaxy: In so far as the plot at $r/r_e < 1.5$ is concerned, the radial gradient of X within the Galaxy appears not to be steep, although there is a tendency to increase with the radius. This is not inconsistent with the result of Bloemen et al. (1986), who found no evidence for a gradient by comparing the γ-ray method data in two bins at $r < 8$ and $r > 8$ kpc. However, if we take into account the outermost data point at 13 kpc in figure 3, as well as the larger value ($X^* = 5.7 \pm 1.0$) obtained for the outer Galaxy at r = 8–10 kpc (r/r_e = 1.2–1.6) by Sodroski (1991), the data appear to infer the existence of a radial gradient in the Galaxy disk. Moreover, a radically smaller value has been derived in the galactic center region by Blitz et al. (1985): $X^*(\mathrm{GC}) < 0.15X^*(\mathrm{disk})$ at $r < 400$ pc, if the γ-ray emissivity is the same as in the disk. They further argue that this smaller value may possibly be due to an unusually high metallicity (CO abundance) as a result of the intense star-formation activity in the galactic center. Hence, by taking into account all of the information so far available for $r \sim 0$ to 13 kpc, we would suggest that the conversion factor may be an increasing function of the galacto-centric distance in the Galaxy disk.

M51: We plotted two independent estimates of X^* for M51 obtained by Adler et al. (1992) based on the virial method, and by Nakai and Kuno (1995) based on the A_V method. Both plots give nearly identical $\log X^*$ vs r/r_e relations. Note that in their A_V method Nakai and Kuno (1995) assumed a constant extinction-to-column density ratio. However, if we assume that the extinction-to-column density ratio increases with decreasing radius (as one would expect from the corresponding increase in metallicity with decreasing radius), one would expect that a systematic overestimate of the H_2 column density (and, thus, an overestimate of X) would be made with decreasing radius. Namely, an even steeper gradient in X would be inferred to exist for a more realistic interstellar condition in M51 than has been found here. We also mention that a factor of 4.5 smaller value than the galactic value has been derived for the central region of M51 from a comparison of the λ 1.2 mm continuum emission by dust and the ^{12}CO ($J = 2$–1) line intensities (Guélin et al. 1995).

Since the radial distribution of X^* in these galaxies merely reflects the radial abundance gradient of oxygen, it is reasonable to have such a tight correlation between X^* and r/r_e. Indeed, Díaz (1989) showed that the oxygen abundance at any galactocentric distance in the disk of a spiral galaxy can be written as

$$\log(\mathrm{O/H}) = \log(\mathrm{O/H})_\mathrm{e} - 0.39(r/r_\mathrm{e} - 1), \qquad (8)$$

where $(\mathrm{O/H})_\mathrm{e}$ is the oxygen abundance at the effective radius of a galaxy. By putting equation (2) into equation (8), we obtain

$$\log X^*/X^*e = 0.39(r/r_\mathrm{e} - 1), \qquad (9)$$

where X^*_e is the conversion factor at the effective radius r_e. This formula requires a knowledge of X^*_e alone, and can be used for any galaxy for which the oxygen - abundance gradient is not actually known. Note that the values of X^*_e of the galaxies shown in figure 3 are nearly identical, which is the reason why one obtains an apparently universal X^* vs r/r_e relation for these galaxies. Of course, if X^*_e for a galaxy is considerably different from the above-studied galaxies, the galaxy should have a different X^* vs r/r_e relation from that shown in figure 3 (e.g., M33). In figure 3 we plot $\log X^*/X^*_\mathrm{e}$ vs r/r_e for the Galaxy, M31, and M51. In fact, a least-squares fit to the data in figure 3 gives

$$\log X^*/X^*_\mathrm{e} = 0.41(r/r_\mathrm{e} - 1). \qquad (10)$$

This fit is consistent with the expected relation using equation (9).

According to the present result, the conversion factor significantly decreases toward the galactic center. The above equation gives a factor of 3 smaller value of the conversion factor in the galactic center compared to the solar-vicinity value. Recentely, Sodroski et al. (1995) obtained a factof of 3 – 10 smaller value of X in the central 400-pc region of the Galaxy than the solar-vicinity value based on an analysis of the far-infrared flux and CO line data. Their result is consistent with the present result. Therefore, the use of the X value from the solar neighborhood to derive the molecular-gas mass in the galactic center would result in an overestimation by a factor of at least three. We emphasize that similar overestimates of the gas mass in the central regions of spiral galaxies would have existed in the observations of spiral galaxies so far observed in the CO-line emission. A correction of the derived gas mass in the central region by applying the present radial dependence would have crucial implication on the disk stability and accretion process related to the central star-forming activity, starburst and gas feeding to the nuclei.

4.3. Chemical Properties of Galaxies and the Conversion Factor

The formula, equation (2), obtained in the previous section has great potential in chemical-evolution studies of disk galaxies. In particular, once the simple model of galactic chemical evolution is assumed, it is possible to derive the distribution of the yield of oxygen, and probably those of other elements, in disk galaxies. The yields of heavy elements are one of the most important properties in chemical-evolution study, since they provide information directly related to the stellar initial-mass function (IMF), and thus to stellar nucleosynthesis. However, except for the solar neighborhood disk of the Milky Way Galaxy, the true yields of heavy elements, such as carbon and oxygen in disk galaxies, are not yet known. A difficulty in obtaining the precise mass distribution of H_2 molecule was the major obstacle for this. To derive the distribution of the yield, one needs to know: 1) the abundance distribution of heavy element, e. g., oxygen, $12 + \log(\mathrm{O/H})$; 2) the stellar-mass surface density Σ_*; 3) H I density distribution $\Sigma_{\mathrm{H\,I}}$, and 4) the H_2 density distribution $\Sigma_{\mathrm{H_2}}$. Σ_* is derived from the surface brightness by assuming that the mass distribution follows the light distribution with a constant mass-to-light M/L ratio. The H_2 distribution has so far been calculated based on the CO distribution by assuming a constant conversion factor (Young, Scoville 1991). Vila-Costas and Edmunds (1992) parametrized the dependence of the conversion factor on the metallicity, and derived the H_2 distributions for more than 30 disk galaxies.

We here propose to use equation (9) to estimate the radial distribution of H_2 molecular gas in disk galaxies. If the radial distribution of oxygen is known, equation (9) gives the distribution of the conversion factor X^*, which one can use to derive the H_2 distribution from the CO data. By defining the gas density fraction, $\mu = \Sigma_{\rm gas}/\Sigma$, as the ratio of total gas mass density ($\Sigma_{\rm gas} = \Sigma_{\rm H\,I} + \Sigma_{\rm H_2}$) to the total density of stars and gas ($\Sigma = \Sigma_{\rm gas} + \Sigma_*$), one finally obtains the yield of oxygen as $y_{\rm O} = -Z({\rm O})/\ln(\mu)$, where $Z({\rm O})$ is the abundance of oxygen in mass, provided that the chemical evolution of disk galaxies at any distance from the galaxy center is described by the so-called simple model (cf. Tinsley 1980). If the IMF is constant in time and space, an identical yield should be obtained at any galactocentric distance. Several attempts have already been made to speculate on the dependence of the yields on the metallicity (Vila-Costas, Edmunds 1992; Henry et al. 1992, 1994). Although these authors suggested a non-linear dependence of the effective yields of oxygen, nitrogen, and sulfur on the metallicity, their speculations depend entirely on the assumed conversion factor X^*. We are re-analyzing the yields of heavy elements in disk galaxies by adopting the new conversion factor with the metallicity dependence derived in the present study; the results will be discussed extensively elsewhere.

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