

The CO Tully-Fisher relation for the Virgo cluster

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Abstract. A comparison between the CO and HI Tully-Fisher relation for a sample of 30 Virgo galaxies shows no significant difference concerning the intrinsic scatter. The distance moduli from both relations after correcting for the sample incompleteness bias agree within the errors and also show no significant difference with previous studies of the Virgo cluster using a complete sample. The CO total linewidth and the CO flux were found to be not well correlated. However, if the distances to the individual galaxies were calculated by the CO Tully-Fisher relation, the CO luminosities calculated using these distances are correlated with the CO linewidths. This correlation does not show up when the distances were calculated by the conventional HI Tully-Fisher relation. Finally we give the structure of the cluster as derived from this small subsample using the distances to the individual galaxies. The large depth of the cluster is confirmed both by the HI and the CO Tully-Fisher relation.

Key words: galaxies: general – galaxies: distance – radio lines: galaxies – galaxies: clusters: Virgo cluster

1. Introduction

The rotational characteristics used in the Tully-Fisher relation so far has mostly been determined by observations of the 21 cm line of atomic hydrogen (Tully & Fisher 1977, Tully & Fouqué 1985, Aaronson et al 1986, Pierce & Tully 1988, Kraan-Korteweg et al. 1988; Fouqué et al. 1990; Fukugita et al. 1991). The use of CO instead of HI was proposed by Dickey & Kazes (1992). Due to the smaller beam in CO compared to HI, the usage of CO could help to overcome the present limit of 50 to 100 Mpc, up to which galaxies are reachable by observations in HI. Dickey and Kazes found a good correlation between CO and HI linewidths for the Coma cluster and showed the hope that CO might be a useful tool for distant galaxies. Sofue (1992) and Schöniger & Sofue (1994) also found a good correlation between CO and HI for field galaxies, despite most of the galaxies in their sample showed peculiarities like interactions or active nuclei. However, so far it has not been studied how the use of CO affects the

intrinsic scatter of the Tully-Fisher relation compared to the use of HI. Besides this important question concerning the reliability and the accuracy of the new method compared to the HI Tully-Fisher relation any comparison between CO and HI linewidths as a distance indicator enlarges our knowledge and may either support the applicability of the new method or shows us its limitations.

In this context and in order to study cluster galaxies instead of field galaxies, we compared the conventional blue Tully-Fisher relation for 30 Virgo cluster galaxies with the corresponding CO Tully-Fisher relation. We also looked for a possible correlation between CO Flux and CO linewidth. Since such a relation might be deteriorated by the depth effect of the cluster, we corrected for the depth effect by calculating CO luminosities from the Tully-Fisher distances. Finally we compared the depth of the cluster along the line of sight by using the Tully-Fisher distances to the individual galaxies as derived from both distance indicators.

2. Data

All data used in our study was taken from the literature. Most of the galaxies in our sample have been observed in CO by Kenney&Young (1988) and Young et al. (1985) using the 14 m antenna of the Five College Radio Astronomy Observatory (HPBW 50''), some have been observed by Stark et al. (1986) using the 7 m antenna at AT & T Bell Laboratories (HPBW 100''). The limiting apparent blue magnitude corrected for inclination and internal absorption of the sample is $B_T^0 = 12.2$. For the Tully-Fisher analysis we have used the CO and HI linewidths at 20% of peak level. Since the 50'' beam of the FCRO antenna is too small to cover the CO emission of most of the galaxies, we have integrated all the detected positions to a total line profile. If the linewidth of the integrated profile was smaller than the linewidth at 50% of peak level as given in Stark et al., we have used the value from the BTL observations to avoid smaller CO linewidths due to any under-sampling of the molecular gas. The blue magnitudes used in the Tully-Fisher analysis were taken from de Vaucouleurs et al. (1991). Inclinations are from Huchtmeier & Richter (1989) and HI linewidths are taken from Bottinelli and Gougenheim (1991). A compilation of the galaxy properties is shown in Table 1.

Table 1. Galaxy properties for our sample galaxies

Galaxy	i [$^\circ$]	B_0^T	S_{CO} [Jy km/s]
NGC 4064	67	11.84	93
NGC 4192	74	10.07	940
NGC 4212	47	11.37	510
NGC 4216	80	10.29	620
NGC 4237	46	12.20	624
NGC 4254	28	10.08	3000
NGC 4293	76	10.95	270
NGC 4298	67	11.62	660
NGC 4302	90	11.39	620
NGC 4303	25	10.07	2280
NGC 4312	78	11.83	160
NGC 4321	28	9.95	3340
NGC 4388	74	10.82	230
NGC 4402	75	11.70	630
NGC 4419	67	11.63	920
NGC 4438	65	10.56	210
NGC 4450	44	10.70	450
NGC 4501	58	9.86	2220
NGC 4527	72	10.65	1810
NGC 4535	43	10.34	1570
NGC 4536	67	10.56	740
NGC 4548	36	10.80	540
NGC 4569	63	9.79	1500
NGC 4571	27	11.75	380
NGC 4579	36	10.23	910
NGC 4647	36	11.83	600
NGC 4651	45	11.10	350
NGC 4654	52	10.75	730
NGC 4689	30	11.37	710
NGC 4698	55	11.26	90

3. Results

3.1. Tully-Fisher analysis for CO and HI

Fig. 1a shows a plot of CO versus HI linewidths for the Virgo cluster galaxies. The correlation is obvious, despite the scatter is larger than for our study of field galaxies (Schöniger and Sofue 1994). In Fig. 1b we show a histogram of the linewidth ratio W_{CO}/W_{HI} . Here the tendency of the CO profiles to be narrower than the corresponding HI profile can clearly be seen. We get $W_{CO}/W_{HI} = 0.92 \pm 0.13$ compared to $W_{CO}/W_{HI} = 0.96 \pm 0.1$ for our study of field galaxies. The question is whether the differences in linewidths between CO and HI improve or deteriorate the Tully-Fisher relation if CO is used instead of HI.

For the Tully-Fisher analysis the linewidths have to be corrected for inclination i . Hereby usually low inclination galaxies are rejected in order to minimize the error introduced by the uncertainty of the inclination. For a galaxy with an inclination of 30° taken from a usually available catalogue the uncertainty in i of $\pm 7^\circ$ in inclination leads to an error of $+0.7$ mag and -0.52 mag

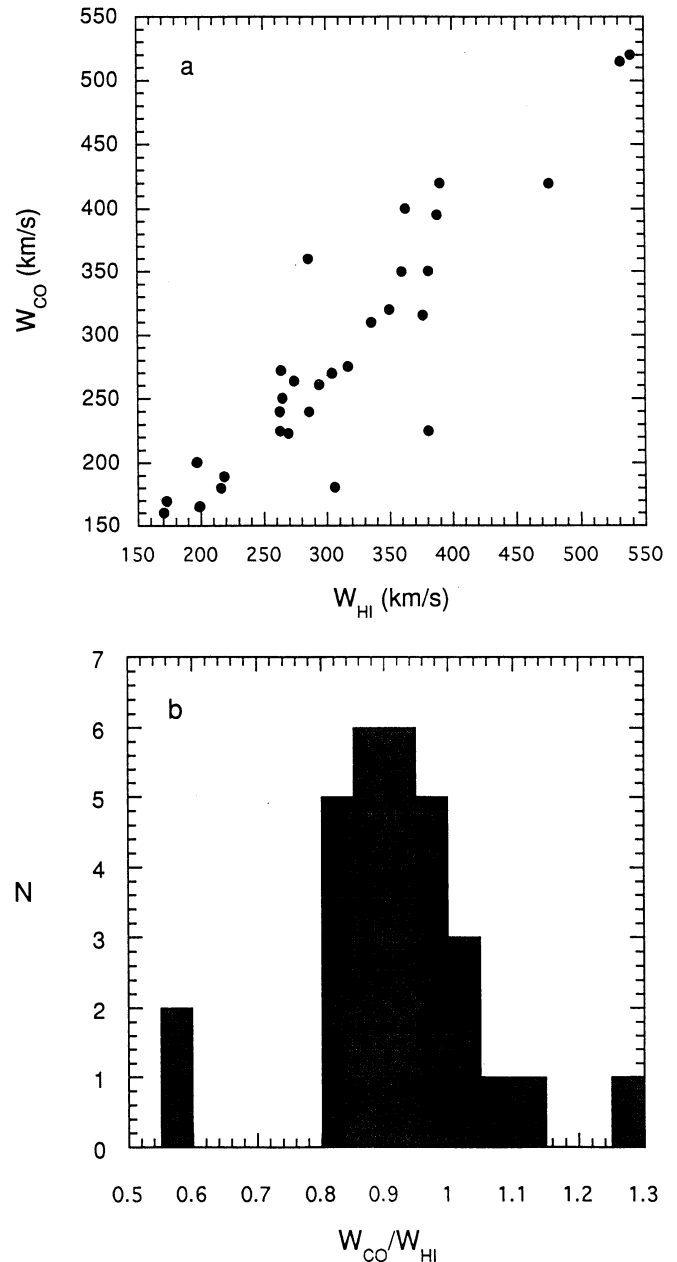


Fig. 1. **a** CO vs HI linewidths and **b** a histogram of galaxy numbers vs W_{CO}/W_{HI}

respectively, which can severely influence a conclusion drawn from the Tully-Fisher relation. In our study we nevertheless do not reject low inclination galaxies. The reason will be explained in detail later when we discuss the influence of the sample incompleteness bias on our result. For the moment we just point out that we wanted to have a sample as complete as possible in linewidths. For the sake of consistency with the most recent and most complete study of the Virgo cluster in the blue band (Fukugita et al. 1993) we did not apply a correction for internal turbulence.

Fig. 2 shows the apparent blue magnitude versus HI linewidths corrected for inclination (Fig. 2a) and versus CO linewidths (Fig. 2b). Low inclination galaxies are marked as

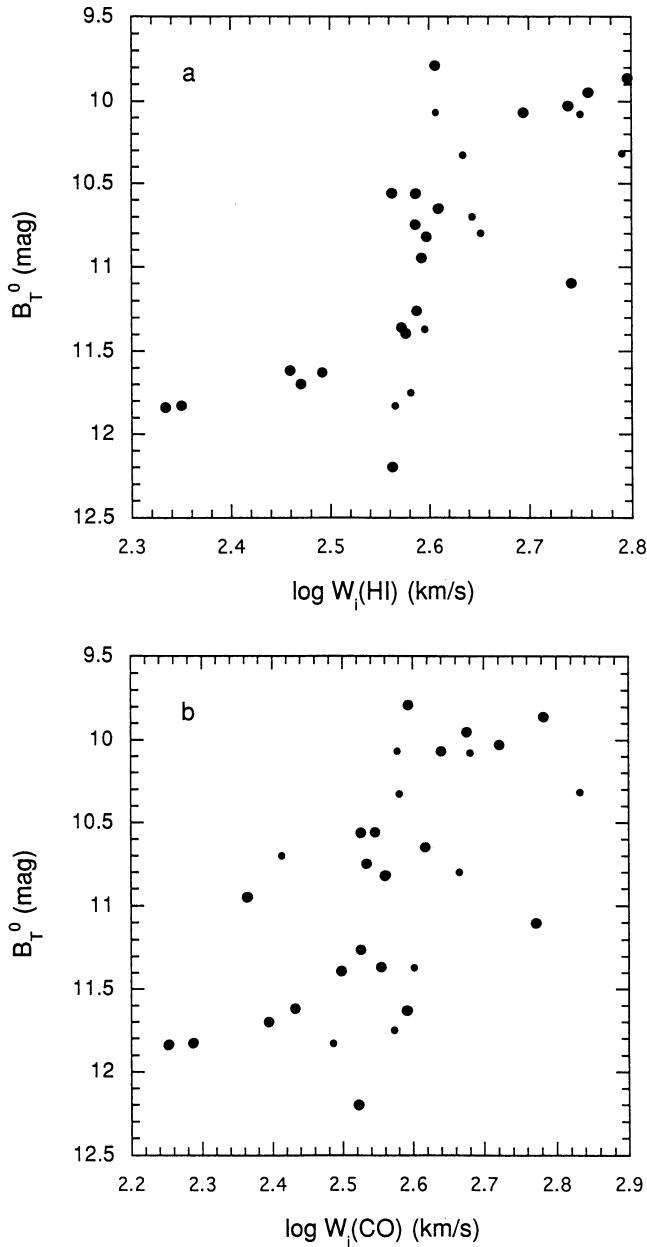


Fig. 2. **a** Blue apparent magnitudes plotted vs HI and **b** CO linewidths, low inclination galaxies ($i < 45^\circ$) are plotted as small dots

smaller dots. The slopes are gentle compared to the slope for the calibrators, -3.05 for the CO and -4.5 for the HI Tully-Fisher relation. The dispersion is 0.52 for the HI Tully-Fisher relation and 0.58 for the CO Tully-Fisher relation. This means that due to the similar intrinsic scatter in case of CO and HI it is difficult to decide which relation gives more accurate distances. Excluding low inclination galaxies does not change this result.

The HI Tully-Fisher relation was calibrated using six local calibrators with Cepheid distances given by Madore and Freedman (1991), yielding:

$$M_B = -(6.31 \pm 0.5)\log W_i - 3.72 \pm 1.24$$

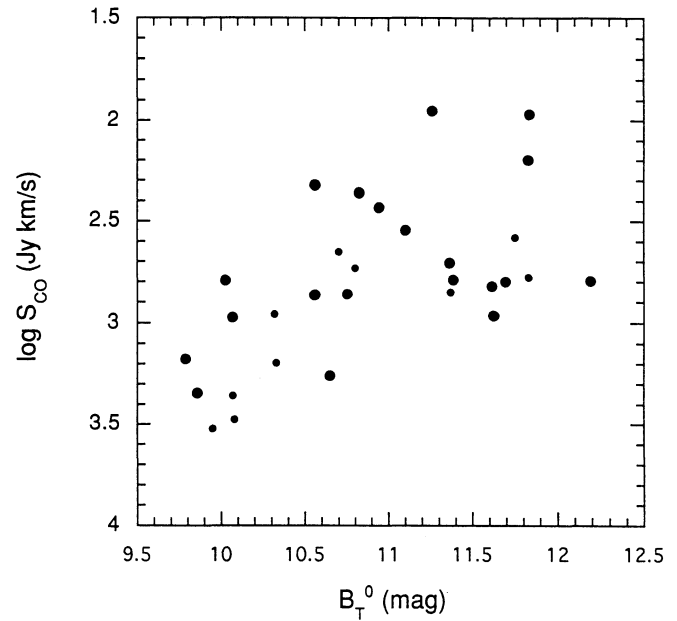


Fig. 3. flux plotted against apparent blue magnitudes. Smaller dots show low inclination galaxies ($i < 45^\circ$).

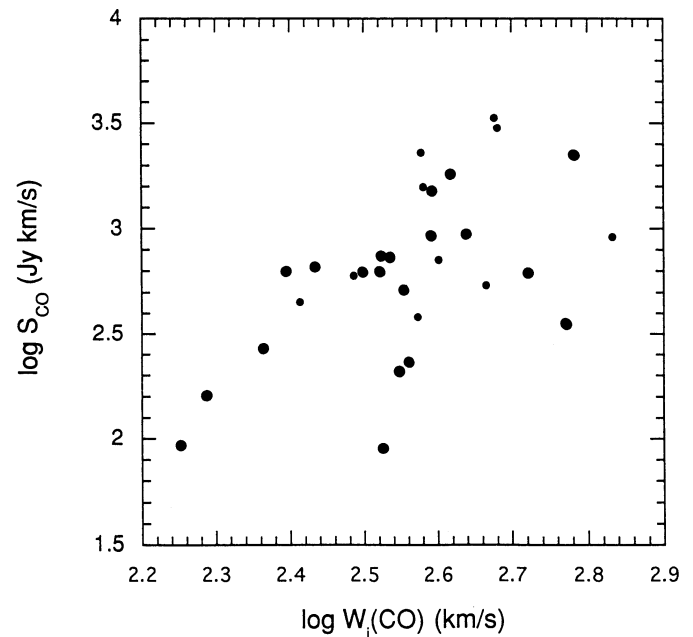


Fig. 4. CO flux plotted against CO linewidths. Smaller dots show low inclination galaxies ($i < 45^\circ$).

Of the local calibrators only M 31 has been completely mapped in CO and a total line profile is available. In case of M 31 the CO and HI profiles agree perfectly. For the other local calibrators we apply the result from our study for field galaxies (Schöniger & Sofue 1994) and adopt a CO total linewidth being four percent smaller than the corresponding HI linewidth. This yields a calibration for the CO Tully-Fisher relation of the form:

$$M_B = -(6.22 \pm 0.5)\log W_i - 4.07 \pm 1.17$$

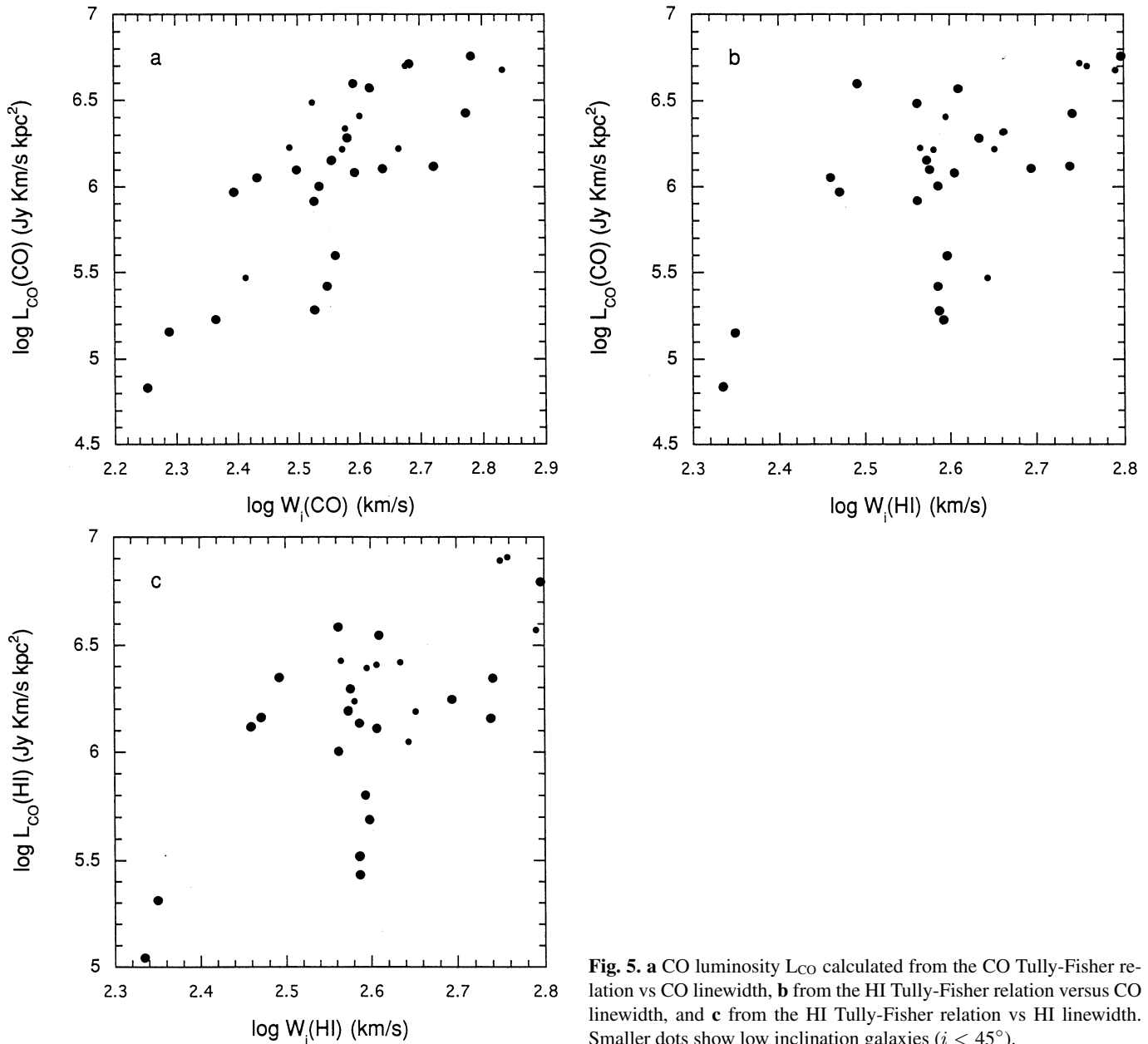


Fig. 5. **a** CO luminosity L_{CO} calculated from the CO Tully-Fisher relation vs CO linewidth, **b** from the HI Tully-Fisher relation versus CO linewidth, and **c** from the HI Tully-Fisher relation vs HI linewidth. Smaller dots show low inclination galaxies ($i < 45^\circ$).

Using this calibrations we get for the cluster distance moduli $(m - M)_0(\text{CO}) = 30.90 \pm 0.70$ and $(m - M)_0(\text{HI}) = 31.03 \pm 0.52$. The smaller distance derived from CO hereby reflects the tendency of the CO linewidths to be narrower than the corresponding HI linewidths.

3.2. Correction for the sample incompleteness bias

An important prerequisite to be able to derive a correct distance from a Tully-Fisher analysis is its application to a complete sample. As pointed out by Teerikorpi (Teerikorpi 1984) any limiting magnitude leads to a more gentle slope in the Tully-Fisher relation and therefore yields a distance smaller than the true value. This sample incompleteness bias or Malmquist bias, as it is also called sometimes, despite not fully correct, has plagued the

Tully-Fisher studies for a long time and led for example Aaronson to the conclusion that the Tully Fisher relation might be curved (Aaronson et al. 1986).

In our case we have a sample complete down to a limiting magnitude of 12.2. This means our result suffers from a severe sample incompleteness bias. This results for example in the gentle slope of the Tully-Fisher relation compared to previous studies using a more complete sample which yield a much steeper slope between 6 and 8. It also leads to the unusually small values for the Virgo distance modulus. In order to alleviate the effect of the sample incompleteness bias we follow a prescription by Schechter (Schechter 1980) who suggested that an unbiased mean distance independent of the limiting magnitude can be derived from the inverse Tully-Fisher relation if the coverage in $\log W_l$ is complete. Since we need a complete-

ness in linewidths to apply this procedure we have not rejected low inclination galaxies. Fouque has demonstrated the applicability of this method for the Virgo cluster (Fouque et al. 1990). Inverse Tully-Fisher relation hereby means that the linewidth is treated as the dependent variable containing all errors. The slope derived this way then is forced onto the calibrators getting the inverse Tully-Fisher relations as follows:

$$M_B = -8.69 \log W_i + 2.09 \pm 0.26$$

in case of HI and

$$M_B = -8.67 \log W_i + 1.92 \pm 0.27$$

in case of CO.

It can be seen that the slopes of CO and HI Tully-Fisher relation now are in agreement. Applying these relations we derive a distance modulus of 31.44 ± 0.70 in case of HI and of 31.18 ± 0.92 in case of the CO Tully-Fisher relation. The result from HI agrees with the result from Fukugita et al. (1993) who also derived a distance modulus of 31.44 from a complete sample. The result from CO still gives a somewhat smaller value, whereas the difference between the two distance moduli even became larger than before applying the correction for the Malmquist bias. Nevertheless also the distance modulus derived from CO increased by almost 0.3 mag due to the application of the inverse relation.

We also checked the effect of restricting our sample to galaxies with inclinations larger than 45° . From the remaining 20 galaxies both relations yield distance moduli 0.2 mag smaller than from the sample including all galaxies. This shows that in order to get a complete coverage in linewidths it is actually necessary to include all galaxies.

Finally we would like to stress again explicitly that despite our study is conducted on a sample which suffers from a severe incompleteness and possibly from under-sampling of the CO emission we were able to derive a distance modulus to the Virgo cluster from the CO observations which disagrees by only 10 percent with previous HI studies using by far larger samples. We can only speculate about the reason for the discrepancy itself, however we can say that it is of an order which still supports an optimistic prospect concerning the future applicability of the Tully-Fisher relation.

This result is particularly important for future applications of the CO Tully-Fisher relation to distant clusters of galaxies which can not be reached by HI. Due to the difficulty of the observations we can hardly expect to be able to observe a complete sample, therefore a correction for the Malmquist bias is essential. The use of the inverse Tully-Fisher relation can help to overcome this problem.

3.3. CO Flux vs CO linewidth

Kenney and Young (1988) in their paper also calculated the total CO flux S_{CO} by fitting the measured intensities at the detected positions to a brightness temperature distribution convoluted

with the telescope beam. CO flux and the observed quantity $\int T_A^* dv$ are related as follows:

$$S_{CO} = \frac{2k}{\lambda^2} \int \int T_{Rav}(\Omega, \nu) d\Omega d\nu$$

whereas $T_{Rav}(\Omega, \nu)$ is the average brightness temperature within the main beam and directly proportional to the antenna temperature T_A^* .

In Fig. 3 we show a plot of the CO flux vs the blue magnitude. Despite the scatter in this plot there is a clear tendency of galaxies being more luminous in the blue having also higher CO fluxes. This actually should also lead to a correlation between CO flux and CO linewidth. In Fig. 4 we have plotted the CO flux versus the CO linewidth for our sample galaxies. The correlation in this plot is not very good; the correlation coefficient is $R = 0.59$. However, since any possible correlation of these quantities could be disturbed by the depth effect of the Virgo cluster, we corrected for the depth effect by plotting luminosities instead of intensities. We calculated the luminosities first using the HI distances and secondly using the distances derived from the CO Tully-Fisher relation, and then plotted them separately versus the HI and CO linewidths.

The result is shown in Fig. 5. The luminosities derived from the CO Tully-Fisher distances are much better correlated with the CO linewidth ($R = 0.79$, Fig. 5a) than the luminosities calculated from the HI Tully-Fisher distances ($R = 0.68$, Fig. 5b). The correlation of the luminosities derived from HI with the HI linewidths ($R = 0.67$, Fig. 5c) is also worse than in Fig. 5a. The good correlation in Fig. 5a would fuel speculations about a possible "self consistent CO Tully-Fisher relation", from which galaxy distances can be derived using only CO observations. However, the correlation only shows up when the CO Tully-Fisher distances are used and therefore first has to be checked also in case of other clusters of galaxies. Also it has to be stated that a correlation between CO luminosity and CO linewidth could introduce a Malmquist bias onto the inverse CO Tully-Fisher relation.

3.4. The Virgo distance and depth

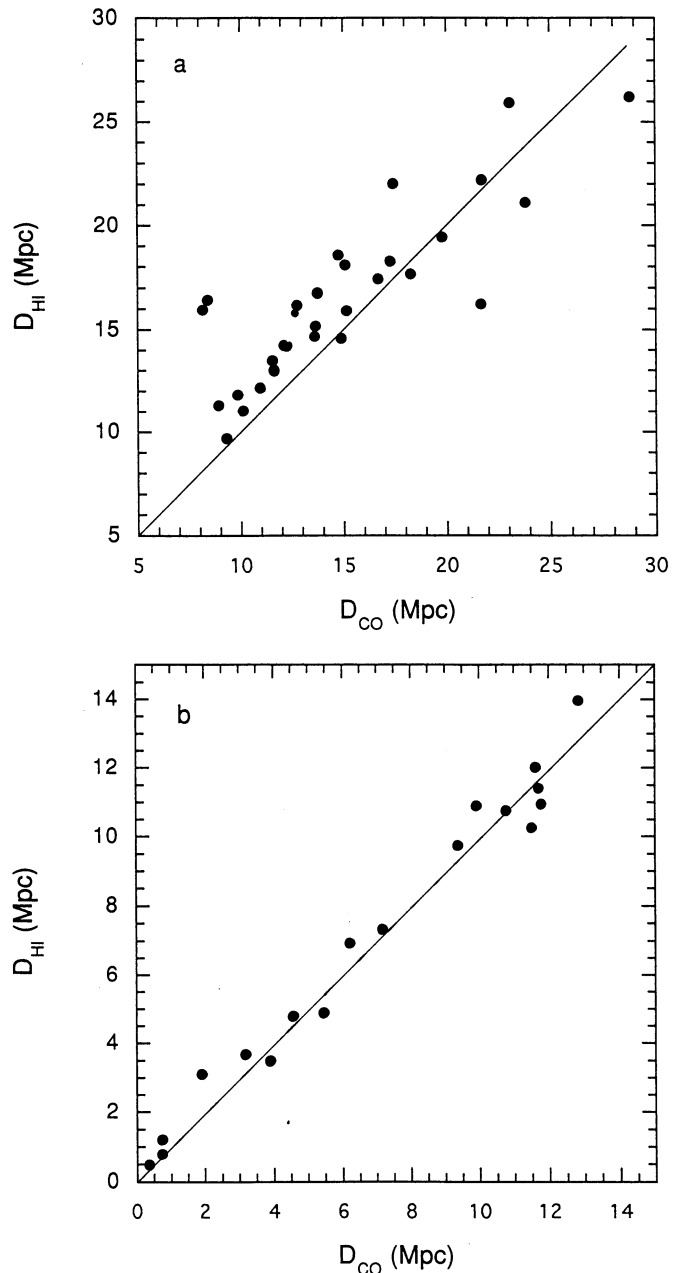
Finally we compare the distances to the individual galaxies using the HI and the CO Tully-Fisher relation. A compilation of the measured linewidths and the resulting distances can be seen in Table 2 and Fig. 6a plots the resulting HI distances versus the corresponding CO distances. The smaller CO distances hereby reflect the tendency of the CO linewidths to be narrower than the corresponding HI linewidths. The HI mean distance is 16.5 ($\sigma = 4.2$) Mpc, while CO value is 15.2 ($\sigma = 5.7$) Mpc. In Fig. 6b we show for comparison the result for normal (non-cluster) galaxies which is reproduced from Schöniger and Sofue (1994). Since the discrepancies are small compared to the errors it is difficult to conclude that the behavior of the cluster galaxies is fundamentally different from field galaxies. However, the tendency to show smaller linewidths in CO than in HI cannot be denied for our sample. For the Coma cluster Dickey and Kazes (1992) found evidence for rather the opposite, therefore

Table 2. CO vs HI linewidths at 20% level, their ratios, and resulting distances for our sample galaxies.

Galaxy	W_{CO}^{20} [km/s]	W_{HI}^{20} [km/s]	$\frac{W_{\text{CO}}}{W_{\text{HI}}}$	D_{CO} [Mpc]	D_{HI} [Mpc]
NGC 4064	165	199	0.83	8.9	11.3
NGC 4192	420	476	0.88	12.2	14.2
NGC 4212	263	274	0.96	17.3	18.2
NGC 4216	520	540	0.96	15.1	15.9
NGC 4237	240	263	0.91	23.1	25.9
NGC 4254	225	264	0.85	13.7	16.8
NGC 4293	240	381	0.59	8.2	15.9
NGC 4298	250	265	0.94	13.6	14.7
NGC 4302	315	377	0.84	14.8	18.5
NGC 4303	160	171	0.94	10.1	11.0
NGC 4312	190	219	0.87	9.8	11.8
NGC 4321	223	269	0.83	12.8	16.2
NGC 4388	350	381	0.92	13.6	15.2
NGC 4402	240	286	0.84	12.6	15.8
NGC 4419	360	286	1.26	21.7	16.2
NGC 4438	320	350	0.91	11.6	13.0
NGC 4450	180	306	0.59	8.4	16.4
NGC 4501	515	532	0.97	16.7	17.4
NGC 4527	395	388	1.01	14.9	14.6
NGC 4535	260	294	0.88	11.5	13.5
NGC 4536	310	336	0.92	11.0	12.1
NGC 4548	272	264	1.03	18.3	17.6
NGC 4569	350	360	0.97	9.3	9.7
NGC 4571	170	173	0.98	21.7	22.2
NGC 4579	400	363	1.10	23.8	21.1
NGC 4647	180	216	0.83	17.5	22.0
NGC 4651	420	390	1.07	28.8	26.2
NGC 4654	270	304	0.89	12.2	14.2
NGC 4689	200	197	1.02	19.8	19.4
NGC 4698	275	317	0.87	13.0	15.0

we have to discuss the possible reasons for this discrepancy, as there were the influence of the cluster environment, the possible under-sampling of the CO emission and a statistical fluctuation.

The smaller CO linewidths compared to HI for our sample are obvious. However, there are only three galaxies which do not follow this trend. For these galaxies, NGC 4438, NGC 4579 and NGC 4651, CO gives a larger distance than HI. These three galaxies are extremely deficient in HI (Kenney & Young 1986) and have almost completely lost their atomic gas due to ram-pressure interaction with the intra cluster medium. The stripping of HI due to ram pressure plays a significant role in the case of the Virgo cluster and the three galaxies mentioned above are extreme examples of this effect. This means that the distances of galaxies which are severely deficient in HI can easily be underestimated by HI and should therefore better be determined by CO. For the galaxies with the larger HI distances another effect must be considered as the origin of the difference between CO and HI linewidths, since ram pressure stripping rather leads to

**Fig. 6.** a CO Tully-Fisher distances plotted against HI Tully-Fisher distances for our Virgo sample and b for our study of field galaxies

smaller HI linewidths than to the larger HI linewidths we actually found. Tidal interactions however can disturb the velocity field of a galaxy in a manner which leads to a wider line profile. Such kind of interaction might be the reason for larger HI linewidths in some cases. However we of course can neither exclude under-sampling of the CO emission as a possible reason nor that its just a statistical effect, since within one sigma the linewidths and distances from HI and CO agree.

We also tried to derive the cluster structure by calculating the distances to the individual galaxies. For this purpose we of course have to use again the direct Tully-Fisher relation which means we are facing again the problem of a poor sample pick-

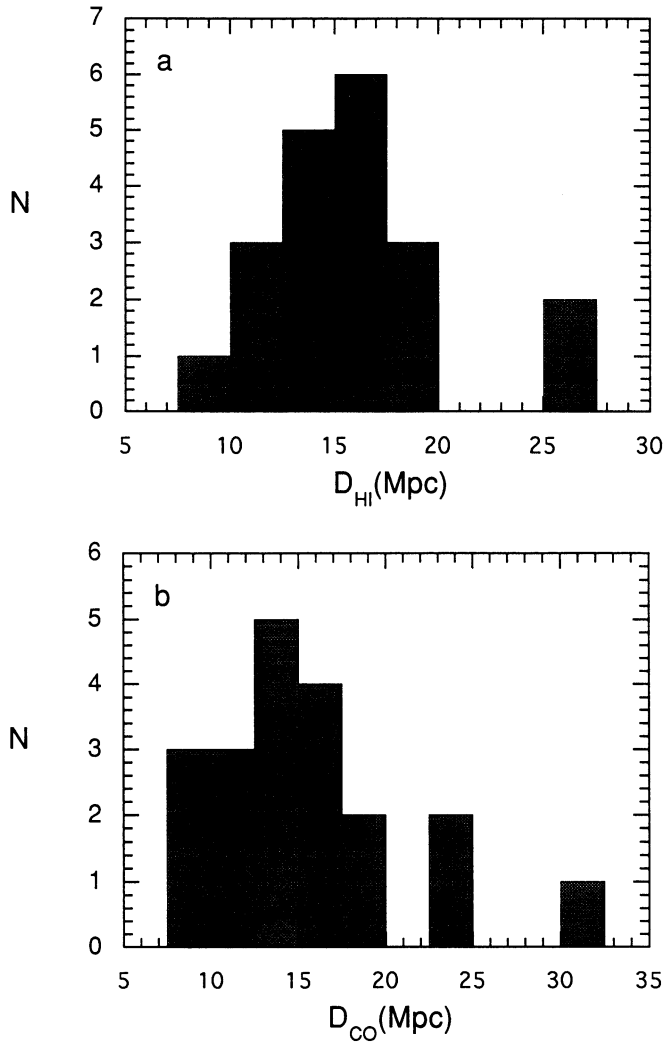


Fig. 7a and b. Histogram of galaxy density as a function of the HI Tully-Fisher distance and **b** CO Tully-Fisher distance

ing out only bright spirals. For this analysis we exclude the low inclination galaxies, since we do not need the complete coverage in linewidths. Of course we cannot expect to derive a detailed structure of the Virgo cluster from such a poor sample. We rather want to look whether the density excess up to distances of about 30 Mpc also shows up in our sample and therefore plotted a galaxy density-distance histogram similar to Fukugita's study.

Fig. 7a shows the galaxy density-distance histogram for the HI Tully-Fisher relation and Fig. 7b for the CO Tully-Fisher relation. As it was found by Fukugita et al (1993), from our small subsample we also can confirm that the individual distances are largely scattered due to the depth effect of the Virgo cluster both in CO and HI determinations and that a density excess exists up to distances of around 30 Mpc. Any further statement about the differences between the two distributions are unjustified due to the poor sample.

4. Conclusion

The intrinsic scatter of CO and HI Tully-Fisher relation for 30 Virgo cluster galaxies turned out to be comparable. The Tully-Fisher analysis yields distance moduli of 31.18 ± 0.92 for the CO Tully-Fisher relation and 31.44 ± 0.70 for the HI Tully-Fisher relation after correcting for the effect of the sample incompleteness bias. Considering the poor sample and the possibly incomplete coverage of the CO emission in some cases the result is in good agreement with previous studies and fuels optimism about the possibility to apply the CO Tully-Fisher relation to distant clusters of galaxies where only a small sample of galaxies can be observed. A correlation between CO luminosity and CO linewidth showed up when applying CO Tully-Fisher distances to derive CO luminosities. The lack of the correlation in case of the application of the HI Tully-Fisher relation is conspicuous and, therefore, the correlation has to be regarded with scepticism and has to be checked in the case of other samples. The depth effect of the Virgo cluster could be demonstrated using the CO as well as the HI Tully-Fisher relation with a result similar to what was derived from a complete sample.

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