IN SEARCH OF A GALAXY SAMPLE TO STUDY THE SYSTEMATIC PROPERTIES OF CO EMISSION FROM GALAXIES

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ABSTRACT. Taking the FCRAO Extragalactic CO Survey as an example, the requirements are examined for a galaxy survey which can be used to study the global molecular gas content of normal galaxies as a function of their size and type. The FCRAO survey is applied to derive the CO luminosity function of galaxies, and to look at variations in L_{CO}/L_B and CO/HI with Hubble type.

1. Introduction

Verter (1987) and Verter (1988) derived some systematic properties of CO emission from galaxies: the luminosity function of galaxies in ^{12}CO, and the correlation between CO emission and other global galaxy properties, respectively. Both of these studies focused on the application of improved statistical procedures, but both were hampered by the quality of the galaxy sample available. The ultimate goal of these statistical studies was to place the molecular gas content of normal galaxies into the framework defined by other global galaxy properties. Principal Component Analysis reveals that 85% of the variance in well-known galaxy properties falls in two dimensions, and can be attributed to the parameters galaxy "scale" and "form" (Whitmore 1984).

This article examines the feasibility of using a galaxy sample drawn from the FCRAO Extragalactic CO Survey (Young *et al.* 1989) to study the global molecular gas content of normal galaxies, as a function of their size and type.

2. The FCRAO Extragalactic CO Survey

The FCRAO survey was chosen to re-evaluate the systematic properties of CO emission from galaxies because it is the largest single survey of global galaxy fluxes. CO observations of galaxies prior to 1985 were cataloged in Verter (1985), and the sequel Verter (1990) contains all published observations that appeared between 1985 - 1989. From Table 2 of the latter catalog, it can be estimated that the FCRAO program has observed at least four times as many galaxies as any other survey.

Galaxies observed in the FCRAO survey were selected by overlapping optical and infrared criteria: the survey aims to cover all galaxies at declinations above -20° which either have $B_T^0 \leq 12$ mag, or IR flux density > a specified threshold in certain IRAS bands. The IRAS threshold has been variously quoted as $F_{100\mu m} = 10$ Jy or $F_{60\mu m} = 5$ Jy (Young *et al.* 1989), or as $F_{100\mu m} = 20$ Jy (Young and Knezek 1989). The FCRAO survey is a multi-year effort which is still ongoing, so analyses using the data collected to date will not represent a complete sample of the selection criteria.

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For this project, FCRAO survey data were taken from Young *et al.* (1989): that compilation contains 107 detections and 16 upper limits on the global CO luminosity, L_{CO}, in units of (Jy km s^{-1} Mpc^2). Many of these global luminosities are based on extrapolations of major axis strip maps; see Kenney and Young (1988a) for details of the extrapolation procedure. All FCRAO survey publications adopt a Hubble constant $H_0 = 50$; in this work everything is on the scale $H_0 = 75$ km s^{-1} Mpc^{-1}.

There is a subtle but important distinction between selecting galaxies based on a brightness threshold and observing galaxies down to a brightness threshold. Only in the latter case can a survey be labelled "magnitude-limited". The observing threshold of the FCRAO survey is $T_{rms} = 10$ mK in spectra smoothed to 12 km s^{-1} resolution (Kenney and Young 1988a). The weakest galaxy line which can be detected at this level depends on the velocity width, and hence the rotation curve and inclination, of the galaxy portion within the beam. Typically, the FCRAO observing threshold corresponds to a 3σ brightness limit of 1 K (T_A^*) km s^{-1} (Kenney and Young 1988a; Young and Knezek 1989).

3. Selection Effects in the FCRAO Extragalactic CO Survey

The selection criteria of a galaxy survey often introduce various biases, or selection effects, which are undesirable. For instance, all magnitude-limited surveys suffer from Malmquist bias, *i.e.,* intrinsically luminous objects are detected throughout a large volume of space, while the actually more numerous faint objects are only detected nearby. This effect is easily characterized and removed by dividing the number of galaxies in each luminosity bin by the volume sampled at that luminosity.

Selecting galaxies for CO observation on the basis of their far-infrared (IR hereafter) emission is not conducive to studying the systematic properties of normal galaxies as a function of size and type. Since the IRAS fluxes of galaxies represent a convolution between a variety of heating sources (young starburst, old stellar population, AGN) and a variety of ISM repositories for dust (GMC's, cirrus clouds, clouds dispersed by a merger, not to mention possible variations in the dust/gas ratio), it is not easy to uniformly or analytically characterize the objects selected by IR criteria.

Moreover, there are two empirical reasons to be wary of IR-selection in CO surveys of galaxies. The first is that the CO and IR luminosities of galaxies are known to be correlated over six orders of magnitude (Tacconi and Young 1987), with the tightest correlation known for CO luminosity (Verter 1988). This implies that IR-selection will bias a CO survey towards the most luminous CO sources. Secondly, it is known that many of the most IR-luminous galaxies are undergoing starbursts and/or mergers (see the review by D.B. Sanders in these proceedings). This implies that IR-selection will bias a CO survey towards interacting galaxies, and therefore will not be representative of normal galaxies.

For the purposes of this project, the FCRAO survey was divided into optically- and IR-selected portions as follows: All galaxies in Young *et al.* (1989) which satisfied the optical threshold $B_T^0 \leq 12$ mag were considered to comprise a complete optically-selected sample (68 detections, 8 upper limits). The remaining galaxies were considered to be an IR-selected appendix to the optical sample (39 detections, 8 upper limits). (Note that the complete sample of galaxies satisfying the IR selection threshold would overlap with the optical sample; the definition adopted here avoids galaxy repetition.) The IR-selected appendix of the FCRAO survey contains some notorious IR-luminous, abnormal, galaxies such as Arp220, NGC6240, and Mk231. In the remainder of this work the optically-selected portion of the FCRAO survey will be used to study the systematic properties of CO emission from normal galaxies.

FIGURE 1 Checks how the FCRAO optically-selected sample covers the range of size and type among normal galaxies. The standard for comparison is provided by Sandage, Binggeli, and Tammann (1985; SBT hereafter), the only work to examine the dependence of optical luminosity functions on galaxy type. In Fig. 1 the absolute magnitudes of the FCRAO galaxies are superimposed on their Fig. 21 which plots the envelope of absolute magnitudes seen among galaxies of a given type. The FCRAO data points are not perfectly alligned with their type bins because the horizontal axis of their figure is not uniformly scaled.

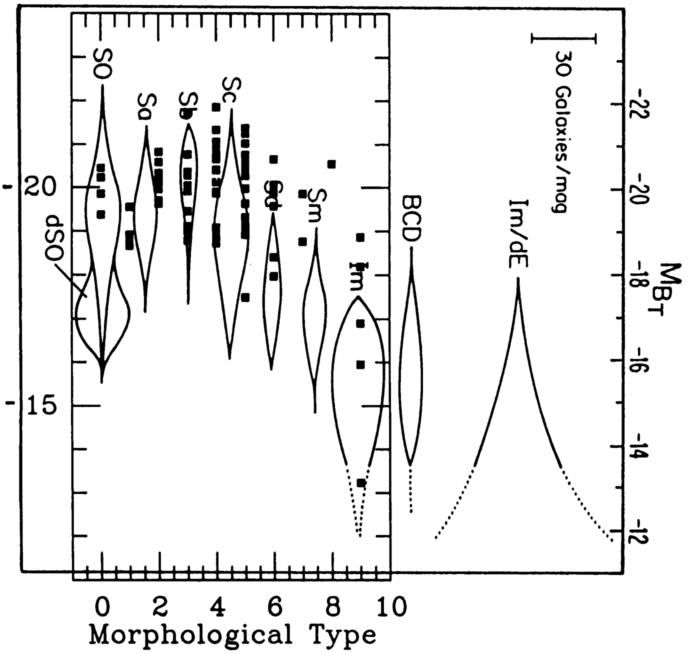


Fig. 1 demonstrates that the optically-selected FCRAO sample only covers the brighter half of galaxies at a given morphological type. Since galaxy size and optical luminosity are very tightly correlated (Whitmore 1984), this is equivalent to covering the bigger galaxies at a given type. This bias is a direct result of the $B_T^0 = 12$ mag survey threshold: most of the galaxies in local space are associated with the Virgo cluster (Haynes and Giovanelli 1983), and $B_T^0 = 12$ is not deep enough to sample the fainter galaxies at the Virgo distance.

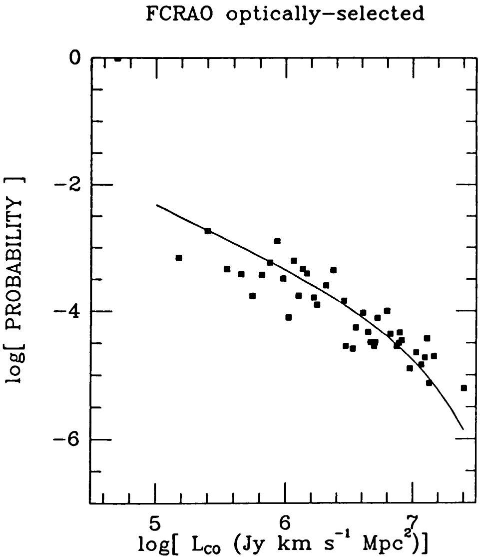
4. CO Luminosity Function of Galaxies

The maximum likelihood CO luminosity function from Verter (1987), incorporating the probability in upper limits and corrections for Malmquist bias, was re-evaluated for the optically-selected portion of the FCRAO survey. Full details of the application to this sample will be given elsewhere (*Ap.J.* article in preparation). We note here that the luminosity function is derived by an iterative formula that procedes from the largest to the smallest luminosity bin, and is normalized to unity. As an artifact of this procedure, the probability tends to jump to near unity in the smallest bin, which should not be interpretted physically.

It is of interest to compare the CO luminosity function with existing galaxy luminosity functions in the blue and IR, because it is well-known that the global CO emission of galaxies (L_{CO}) correlates to their blue luminosity (L_B) and IR luminosity (L_{IR}) (see Verter 1988 and references therein). This is a predictable result of the adage that "bigger galaxies have more of everything". It is also generally expected that L_{CO} traces numbers of warm molecular clouds, and thus should agree with tracers of star-formation (SF). In this sense the correlations of L_{CO} with L_B and L_{IR} are predicted since, in uncomplicated systems such as Irr galaxies, it can be shown that L_B traces stellar populations formed over the past few billion years (Gallagher, Hunter, and Tutukov 1984), and L_{IR} traces stellar populations of all ages (Hunter *et al.* 1989).

Luminosity functions of normal galaxies in the blue (Schechter 1976) and IR-luminous galaxies in the IR (Soifer *et al.* 1987) are compared in Fig. 10 of Soifer *et al.* (1987). Both distributions have characteristic luminosities, " L^* ", at which the slowly declining function turns over and begins to drop rapidly with increasing luminosity. Blue luminosities of galaxies in the FCRAO optically-selected sample are consistent with a Schechter luminosity function having $L_B^* = 3.9 \times 10^{10}\ L_\odot$, as found for the Virgo sample by SBT. There is also a tight correlation between L_{CO} and L_B in the FCRAO optically-selected sample; on the basis of this and the L_B luminosity function, we can predict that the CO luminosity function should turn over at $L_{CO}^* = 9.6 \times 10^6$ Jy km s^{-1} Mpc^2.

FIGURE 2 is a log-log display of the CO luminosity function for the FCRAO optically-selected sample. Galaxies in this sample ranged from $L_{CO} = 1.9 \times 10^2$ to 2.5×10^7 Jy km s^{-1} Mpc^2. The luminosity function was evaluated in bins of width 10^5 Jy km s^{-1} Mpc^2; only non-zero bins (*i.e.*, those containing detections) are plotted. Superimposed is a Schechter (1976) luminosity function which is a -1 power law at low L_{CO}, turns over at $L_{CO}^* = 9.6 \times 10^6$, and drops exponentially at high L_{CO}.



The most notable feature of the derived CO luminosity function is that it is approximately a power law; although this method does not specify the absolute scale of the function, the space density of L_{CO} is proportional to $1/L_{CO}$. This shape is not an artifact of the iteration procedure. Whereas Verter (1987) obtained a mean global CO luminosity of $< L_{CO} >= 1.1 \times 10^6$, this galaxy sample which goes over an order of magnitude fainter has $< L_{CO} >= 6.3 \times 10^4$ Jy km s^{-1} Mpc^2.

The CO luminosity function cannot maintain its L^{-1} power law indefinitely. In order to avoid Olber's paradox, the integral of luminosity over space density must be finite (fundamentals of luminosity functions are reviewed by Dickey 1988). This requires that at high L the density drop more rapidly than L^{-1}. The luminosity function in Fig. 2 seems to be consistent with the turn-over predicted by the correlation with the L_B Schechter function, but the number statistics are too poor to be sure. Only 8 galaxies in the FCRAO optically-selected sample are brighter than the predicted L^*_{CO}.

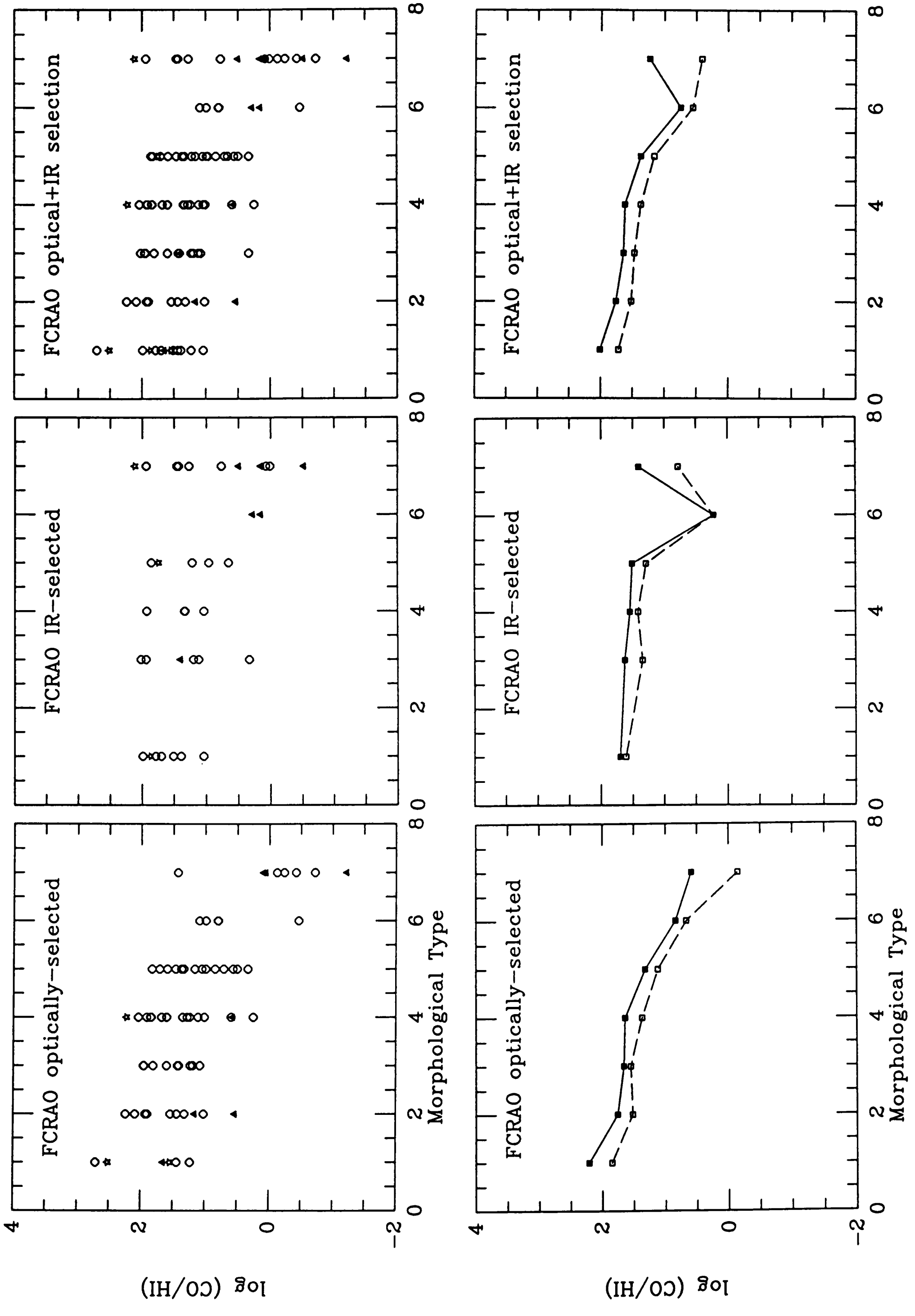
Instead of, or in addition to, changing shape at a turn-over luminosity L^*_{CO}, the CO luminosity function may cut off at maximum and minimum L_{CO} values, corresponding to the maximum and minimum gas contents of normal galaxies. While spiral galaxies are characterized by a limited size range (SBT) and minimum gas content (Corbelli, Salpeter, and Dickey 1990), this luminosity funtion also includes irregular galaxies for which the size range extends down to the HII-region scale (SBT), whose total space density may be underestimated in existing surveys (Tyson and Scalo 1988), and where low $L_{CO}/M(H_2)$ ratios may cause arbitrarily small L_{CO} values (Verter 1987). The extension of the CO luminosity function to small galaxies will be addressed further in the *Ap.J.* article on this study.

5. Dependence of CO Luminosity on Morphological Type

In addition to galaxy size, the second fundamental parameter which accounts for a large fraction of the variation in galaxy properties is galaxy form, or morphological type (Whitmore 1984). It is known that both the atomic hydrogen content and the current star formation (SF) rate of galaxies increases with Hubble type (Roberts 1975; Kennicutt 1983; respectively). It is therefore of interest to see how CO luminosity, as a tracer of molecular hydrogen content, varies with Hubble type.

The ratio L_{CO}/L_B, which normalizes the CO luminosity for galaxy size variations, peaks at intermediate morphological types in the FCRAO optically-selected sample. L_{CO}/L_B rises by a factor of 4 between the earliest types and the Sbc galaxies, then drops by a factor of 5 between the Sbc galaxies and the latest types. In this sample there is over an order of magnitude scatter in L_{CO}/L_B in each type bin, so it is perhaps not surprising that some authors have seen no significant L_{CO}/L_B variation with type (Heckman *et al.* 1989; Young and Knezek 1989). The Heckman *et al.* (1989) sample compared RSA Seyferts with normal galaxies in the literature; the Young and Knezek (1989) sample contained FCRAO survey galaxies. We will return to the importance of sample selection in trends of CO emission with galaxy type.

The existence of a peak in L_{CO} at intermediate galaxy type might seem inconsistent with the overall rise in SF with type. But recent studies suggest that SF efficiency is independent of whether the total gas density is in the atomic or molecular phase (Kenney and Young 1988b; Kennicutt 1989). It is a very interesting question at present to disentangle the physics controlling the accumulation of gas in molecular clouds from the physics that triggers star formation.


FCRAO optically-selected
FCRAO IR-selected
FCRAO optical+IR selection
log (CO/HI)
Morphological Type
4
2
0
−2
0
2
4
6
8

Because of its importance to studies of SF efficiency, this section plots (Fig. 3) the dependence of CO/HI flux ratio on morphological type. Presuming the conversion from CO emission to molecular mass does not vary much among galaxies, this ratio measures the gas phase. In their study of 142 FCRAO survey galaxies, Young and Knezek (1989; see their Fig. 1) show that the H_2/HI mass ratio drops by a factor of 20 from early to late morphological types. For their mass calculation, the corresponding drop in CO/HI is roughly 17.

FIGURE 3 plots CO/HI versus morphological type for several subsets of the FCRAO survey data published in Young *et al.* (1989). Only galaxies which could be assigned normal morphological types are plotted, thereby excluding obvious mergers in the IR-selected appendix (*e.g.,* Arp 220, NGC6240, Arp 55, NGC520, etc.). For purposes of comparison, morphological types are binned as in Young and Knezek (1989): Type 1 = S0-Sa, 2 = Sab, 3 = Sb, 4 = Sbc, 5 = Sc, 6 = Scd, and 7 = Sd - dI. (*i.e.,* to obtain better number statistics, the earliest and latest bins cover more than one type). In the upper panels, the individual galaxy ratios are plotted for detections (open circles), upper limits (filled triangles), and lower limits (open stars). As with L_{CO}/L_B, there is over an order of magnitude scatter in each type bin. In the lower panels, the solid line gives the log of the mean of the points, while the dashed line gives the mean of the logs of the points. Upper and lower limits were included in the means at the limit value. Young and Knezek (1989) claim the error bar on each H_2/HI mass ratio is 42%. From left to right, the panels of Fig. 3 show that the drop in CO/HI from early to late morphological type is a factor of: 42 for the optically-selected sample, 2 for the IR-selected sample, and 6 for the total optical+IR-selected sample.

Not only do the different subsets of the FCRAO survey show different drops in CO/HI with type, but the net sample in Fig. 3 differs from the FCRAO survey data in Fig. 1 of Young and Knezek (1989). Recall that the IR selection threshold in Young *et al.* (1989) is $F_{100\mu m} > 10$ Jy or $F_{60\mu m} > 5$ Jy, whereas Young and Knezek (1989) select $F_{100\mu m} > 20$ Jy. Clearly the sample selection can make an order of magnitude difference in the derived systematic properties of galaxies.

The sensitivity of CO properties in this study to optical versus IR sample selection is not easily explained by other known trends in CO emission properties. In particular, Mirabel and Sanders (1989) have shown that CO/HI is well correlated to L_{IR}/L_B for the IR-luminous galaxies in Soifer *et al.* (1987), and Heckman *et al.* (1989) also find CO/HI is higher in Seyferts than in normal galaxies. It is tempting to presume that CO/HI does not drop as rapidly with type in the FCRAO IR-selected sample because some of the later galaxies have higher L_{IR}/L_B ratios. This is not the case. Although CO/HI does increase with L_{IR}/L_B in the FCRAO IR-selected sample, all of the L_{IR}/L_B ratios are below the "excess" range explored by Mirabel and Sanders (1989), and, consistent with the findings of Hunter *et al.* (1989), there is no trend in L_{IR}/L_B with type.

6. Summary

1) To date, the best source of total CO luminosities for statistical studies of galaxies is the FCRAO Extragalactic CO Survey. Although this article has criticized the survey, it should be emphasized that it is the best sample we have, that it has been compiled at the expense of much telescope time and great effort by many people, and that it should be continued.

2) The FCRAO survey uses overlapping optical and IR criteria to select galaxies for observation. A limitation of IR selection is that it includes many abnormal galaxies which are

distant mergers. A limitation of the current optical selection threshold ($B_T^0 = 12$ mag) is that it only covers the brighter/bigger half of nearby normal galaxies.

3) The CO luminosity function of galaxies in the FCRAO optically-selected sample is roughly a power law: the space density of galaxies keeps rising at faint L_{CO} roughly as $1/L_{CO}$.

4) The range of L_{CO} covered by surveys of normal galaxies needs to be extended. At the bright end, better number statistics are needed to see if the CO luminosity function turns over as predicted by the correlation of L_{CO} and L_B. At the faint end, it is of interest to see if small galaxies obey the same luminosity function as the bigger ones in the FCRAO optically-selected sample.

5) The dependence of CO emission on morphological type, whether it is normalized to galaxy size (L_{CO}/L_B) or expressed as gas phase (CO/HI), varies when samples are selected by optical criteria (tracing galaxy size) or infrared criteria (tracing star formation, if there is not a large AGN contribution). Until these differences are better understood, it is not advisable to mix optical and infrared selection criteria when constructing galaxy samples for statistical study.

6) Future survey work could observe the global CO luminosity from normal galaxies over their full range of size and type by extending the FCRAO survey to a deeper optical selection threshold. For example, SBT obtained full size and type coverage by selecting all Virgo galaxies above the optical threshold $B_T^0 = 18$ mag. But their sample was 856 galaxies; a more practical CO survey would be to make selective extensions of the FCRAO sample to improve the coverage of small galaxies, especially non-starbursting dwarfs.

7) Alternatively, future survey work might aim to compile a CO equivalent of the Haynes and Giovanelli (1984) HI survey of isolated galaxies. Such a sample does not exist at present (as noted by Kenney and Young 1988a). This would require observation of 324 galaxies covering a wide range of size, type, and distance.

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