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A Basic Step toward the CO-Line Tully-Fisher Relation

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Abstract

Composite total line profiles of the CO line emission from two typical edge-on galaxies, NGC 891 and NGC 4565, were found to coincide almost perfectly with their total H I line profiles. Even for peculiar and disturbed edge-on galaxies, like NGC 4631 and NGC 3079, an approximate coincidence between the H I and CO profiles has been found. We argue that CO line emission is a promising alternative to H I for the Tully-Fisher relation.

Key words: CO line emission — Cosmology — Distances — Galaxies — Tully-Fisher relation

1. Introduction

The Tully-Fisher relation is one of the most powerful tools used to estimate distances to galaxies (Tully and Fisher 1977; Aaronson et al. 1986; Pierce and Tully 1988; Kraan-Korteweg et al. 1988; Fouqué et al. 1990; Fukugita et al. 1991). In spite of many different photometric techniques (see the literature mentioned above), almost identical H I data have been used (e.g., Huchtmeier et al. 1989; Bottinelli et al. 1990), except for a Tully-Fisher relation study using Hα rotation curves instead of the H I line width (e.g., Mathewson et al. 1992). The distances to galaxies so far reached by H I observations have been limited to around 100 Mpc, or recession velocities of about 10,000 km s^{-1}, even using the largest telescope (Dickey and Kazès 1992).

Recently, Dickey and Kazès (1992) addressed the question whether linewidths in CO line emission ($\lambda = 2.6$ and 1.3 mm) can be used in the Tully-Fisher relation as an alternative or supplement to H I. Based on their new mm CO observations, they found a linear correlation between the CO and H I linewidths for member galaxies of the Coma and other nearby clusters of galaxies, and showed the possibility that the CO Tully-Fisher relation can be useful for galaxies in distant clusters. The most powerful existing telescopes used for this purpose are the Nobeyama 45-m and IRAM 30-m telescopes, which are operational at the CO-line mm wavelengths and have beam widths of 15″ and 21″ for the J = 1–0 line, respectively. Because of the small beams, the CO Tully-Fisher relation is most useful for galaxies beyond 20,000 to 30,000 km s^{-1}. Moreover, CO emission has an intrinsically higher brightness temperature than that of H I; further, another hope for the CO Tully-Fisher relation is that mm-wave techniques will be greatly improved in the near future.

In this *Letter* we address the following basic questions, which have been touched upon by Dickey and Kazès (1992), but which have not yet been clearly answered: Why are the CO and H I line widths correlated with each other? More specifically, are individual total CO and H I line profiles similar or identical to each other? If so, what is the reason? These basic questions can be answered by comparing detailed CO and H I line data for nearby galaxies. Since the rotation characteristics of galaxies are concerned, edge-on galaxies, for which errors arising from the inclination uncertainty bocome negligible, are preferable for this study. We therefore analyzed the CO line profiles for the following nearest, almost perfect edge-on galaxies: NGC 891, NGC 4565, NGC 4631 and NGC 3079. We used high-sensitivity CO line data from the Nobeyama 45-m telescope and mm Array (e.g., Sofue and Irwin 1992; Sofue et al. 1993; Sofue and Nakai 1993), and compared them with H I line profiles from the literature.

2. Total CO vs H I Line Profiles

Observations of the ^{12}CO(J = 1–0) emission line from four edge-on galaxies were carried out using the Nobeyama 45-m telescope at a resolution of 15″ during the course of a high-sensitivity, high-resolution CO line survey of edge-on galaxies. Detailed descriptions of the observations and data analysis have been given in a series of papers (Sofue et al. 1989; Sofue et al. 1993; Sofue and Nakai 1993). These papers and the literature contained therein can be referred to for such parameters as the distances of the galaxies. Here, we used the CO line profiles observed along the major axis of each galaxy, and integrated them to obtain a single total profile. The results are given in figure 1 along with H I line profiles taken from the literature (Rots 1980; Rupen 1991; Irwin and Seaquist 1991).

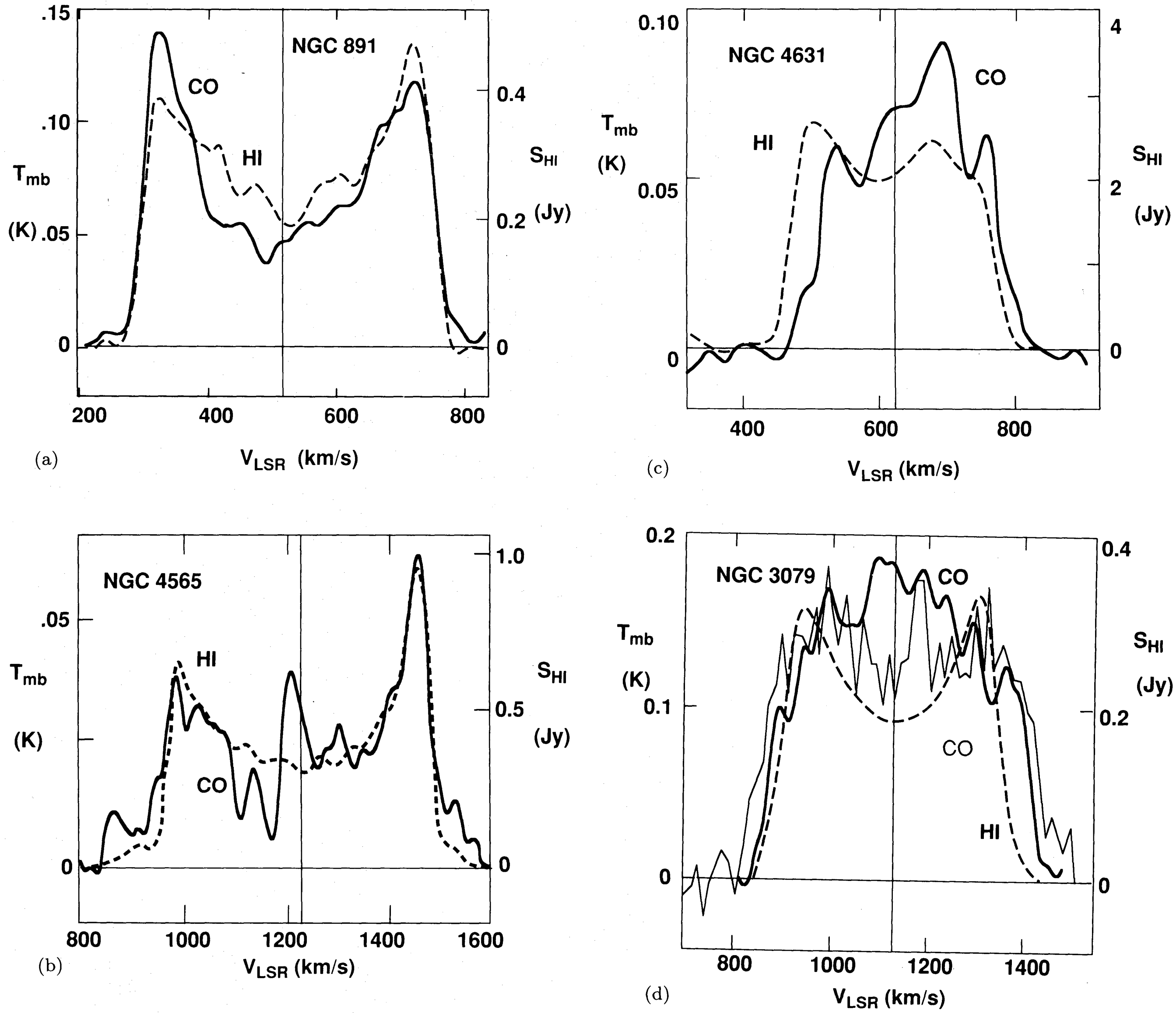

Fig. 1. Total line profiles of the ^{12}CO(J = 1–0) line emission observed with the 45-m telescope (full line), and H I (dashed line: Rots 1980; Irwin and Seaquist 1991) for edge-on galaxies: (a) NGC 891; (b) NGC 4565; (c) NGC 4631; and (d) NGC 3079. The thin-line in (d) is a CO profile obtained with the Nobeyama mm Array, where the full intensity scale is 0.5 K in $T_{\rm mb}$. The vertical lines indicate systemic velocities.

NGC 891: This is a typical, "standard" edge-on galaxy of the Sb type; it is isolated and not disturbed (e.g., Sandage 1961). A CO line scan was carried out over the range of $5' > X > -4.'5$ (for ±13 kpc at a distance of 8.9 Mpc), where X is the distance from the galactic center along the galactic plane (major axis) with positive values in the eastern half of the galaxy. The result is given in figure 1a, together with an H I profile taken from Rots (1980). The CO intensity is the main-beam brightness temperature ($T_{\rm mb}$) averaged over the scanned region, which was equivalent to the brightness temperature when the galaxy was observed with an elongated beam of $9.'75 \times 15''$ (25 kpc × 0.67 kpc). We found an almost perfect coincidence between the CO and H I profiles, except for a slight asymmetry with respect to the systemic velocity: both lines show an almost identical double-horn profile, typical of a rotating ring of a flat rotation curve. The full widths at half maximum intensity for the both lines are the same within the error of data (FWHM $= 460 \pm 10$ km s^{-1}).

NGC 4565: This is also a "standard" edge-on galaxy of the Sb type, without any sign of interaction and warping. CO scan data for $3.'25 > X > -3.'25$ (±9.5 kpc at 10 Mpc distance) are used; the result is shown in figure

1b superposed by an H I profile (Rots 1980). The CO intensity indicated in this figure is $T_{\rm mb}$ when the galaxy was observed with an effective beam of $6.'75 \times 15''$ (20 kpc $\times$ 0.73 kpc). Again, we found almost identical line profiles for both CO and H I, even including the lobsidedness with respect to the systemic velocity. Both the H I and CO profiles are associated with a high-velocity wing at its 10–20% level, with the CO wing being slightly stronger. The FWHMs ($= 500 \pm 10$ km s^{-1}) for both species are equal to each other within the error.

NGC 4631: This is a peculiar, interacting edge-on galaxy of the Sc type; its morphology is rather amorphous (Sandage 1961). CO scan data from Sofue et al. (1989) for $1'40'' > X > -1'40''$ ($\pm$2.52 kpc for 5.2 Mpc distance) are used; the result is shown in figure 1c along with an H I profile (Rots 1980). The indicated intensity is $T_{\rm mb}$ when the galaxy was observed with a $3'35'' \times 15''$ (5.4 kpc $\times$ 0.38 kpc) beam. The CO emission was detected only over a limited region within 2 kpc of the galactic center; the data cover almost the entire CO emitting region (Sofue et al. 1989). Both the H I and CO profiles have a similar double-horn + central-peak structure. The H I systemic velocity is blue-shifted by about 20 km s^{-1} from CO, which may be due to a tidal disturbance on the outer H I gas (Weliachew et al. 1978). This may be confirmed by the fact that the CO systemic velocity is closer to the optical systemic velocity. The H I line width (FWHM $= 300 \pm 10$ km s^{-1}) is broader than CO (260 ± 10 km s^{-1}), which may be also due to a tidal disturbance on the H I envelope.

NGC 3079: This amorphous edge-on galaxy is known due to its vertical radio lobes as well as its variety of activity (e.g., Duric et al. 1983). CO gas is highly concentrated near the nucleus, displaying a high-velocity dispersion (Young et al. 1988; Sofue and Irwin 1992). CO scan data for $30'' > X > -30''$ ($\pm$2.2 kpc for 15 Mpc distance: $H_0 = 75$ km s^{-1} Mpc^{-1}) are used; the result is shown in figure 1d, where the velocity resolution is about 10 km s^{-1}. The intensity is $T_{\rm mb}$ for an effective beam of $1.'25 \times 15''$ (5.5 kpc $\times$ 1.1 kpc). We also show the total profile constructed from a position-velocity diagram along the major axis, obtained using the Nobeyama mm Array (NMA) (Sofue and Irwin 1992), where the effective beam is $1' \times 4''$ (4.4 kpc $\times$ 0.29 kpc). An H I profile is reproduced from Irwin and Seaquist (1991). The CO profile is rather round, while the H I profile has double horns. The CO widths (FWHM $= 515 \pm 10$ km s^{-1} for CO from 45-m telescope; 540 ± 10 km s^{-1} from NMA) are broader than that of H I (FWHM $= 450 \pm 10$ km s^{-1}).

3. Discussion

The CO line profiles coincide with the H I profiles. In particular, an almost perfect coincidence is found in such non-disturbed galaxies as NGC 891 and NGC 4565. In some cases, however, the CO profiles are associated with a high-velocity wing, that extends tens of km s^{-1} beyond the double-horn edges, due to a rapidly rotating, or high-dispersion, innermost disk (Sofue et al. 1993; Sofue and Nakai 1993). Due to this wing component, the full line width near zero intensity (e.g., 20%-level width) is slightly larger in CO than in H I. We, therefore, used the FWHM (50%-level line width) instead of the 20%-level width. We would propose that FWHM should be more preferably used for the CO Tully-Fisher relation, rather than the 20%-level width.

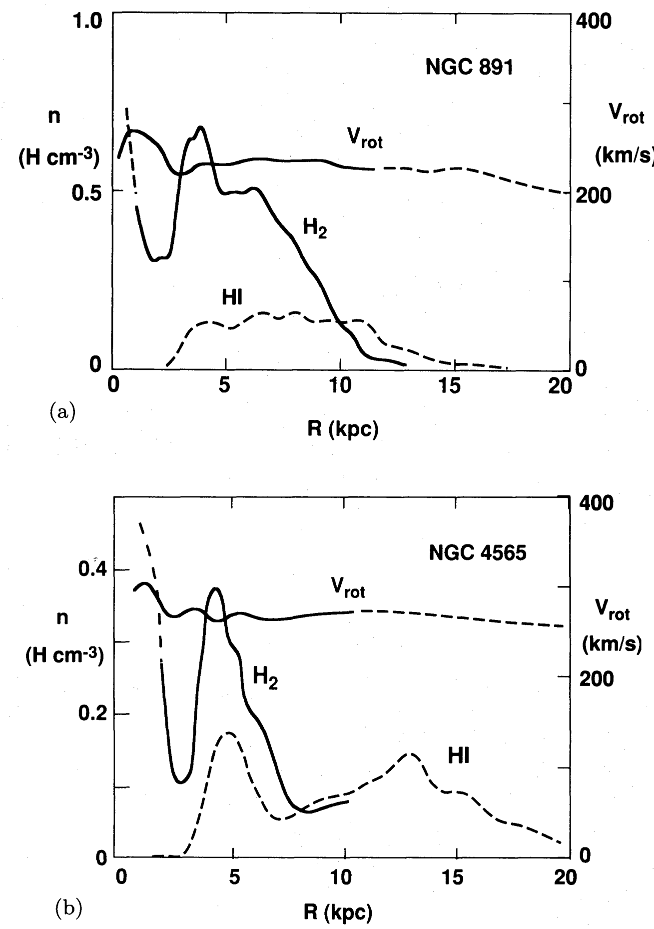

Fig. 2. Radial distributions of the H_2 and H I gas densities for (a) NGC 891; and (b) NGC 4565. Their CO and H I (Rupen 1991) rotation curves are indicated by the thick and dashed lines, respectively.

We next consider the reason why almost identical line shapes in CO and H I are observed in galaxies NGC 891 and NGC 4565, based on the rotation curves and CO/H I radial density distributions (Sofue et al. 1993; Sofue and Nakai 1993), which are shown in figure 2.

Genarally, the rotation curves are almost flat beyond

1 kpc from the galactic center, attaining a broad maximum at around a galactocentric distance of $R \sim$ 3–5 kpc. The rotation and/or dispersion is higher in the central few hundred pc, which contributes to the high-velocity wing in the total profile. The radial distribution of CO gas has two major density maxima: one near the center and the other at around $R \sim$ 3.4 and 4.5 kpc for NGC 891 and NGC 4565, respectively. When the line emission is integrated over an entire galaxy, the contribution from the outer ring/disk becomes dominant, since the total amount of gas involved in the outer ring/disk is much larger than that in the central region, simply for the disk's surface-area effect. Hence, the ring/disk component becomes the major source for the total line profile.

Although H I gas is distributed over a broader disk than CO, its densest region is close to the CO disk (figure 2). Namely, the densest H I disk appears at 3–10 kpc for NGC 891 and at 5–10 kpc for NGC 4565. Moreover, the rotation curve attains its broad (nearly flat) maximum at these radii. Hence, the CO and H I double horns arise from almost the same radii, where the rotation curve is nearly flat.

These arguments may also apply to other galaxies, NGC 3079 and NGC 4631, which exhibit some peculiar features. The molecular gas in NGC 3079 is unusually concentrated toward the nucleus, exhibiting a high-velocity rotation. The radial H I distribution in NGC 3079 shows also an exceptionally high concentration toward the center (Irwin and Seaquist 1991), and would exhibit the same rotation characteristics as the central CO rotation.

The H I disk of NGC 4631 is tidally disturbed (Weliachew et al. 1978), which may be the cause for the larger width in H I than in CO. In such a disturbed galaxy, in which the outer H I disk is more strongly disturbed than the inner CO disk, the CO profile may better represent the true rotation-characteristics of the major part of the galaxian disk. This implies that the CO Tully-Fisher relation may be more reliable for interacting galaxies. Since most galaxies belong to groups or clusters, and therefore, most galaxies are interacting, experiencing a tidal disturbance. This implies that the CO Tully-Fisher relation would be a better alternative than H I for nearly all galaxies. The line-width difference between H I and CO could be used as an indicator of disturbed velocity field; this could be used to reject peculiar galaxies which do not satisfy the Tully-Fisher relation.

Finally we stress that the CO/H I line-width correlation, even for the two peculiar galaxies NGC 4631 and NGC 3079, is comparable to that for the H I vs CO width plot obtained for the best samples given by Dickey and Kazès (1992); of course, standard galaxies NGC 891 and NGC 4565 show an almost perfect correlation.

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