DETERMINATION OF THE SPIRAL PATTERN SPEED OF THE GALAXY

M. A. GORDON

National Radio Astronomy Observatory,* Green Bank, West Virginia

Received 1977 November 3; accepted 1977 November 23

ABSTRACT

The carbon monoxide abundance as a function of galactocentric radius, in conjunction with a newly determined galactic rotation curve, gives a spiral pattern speed of $11.5 \pm 1.5 \text{ km s}^{-1} \text{kpc}^{-1}$. This value is based upon the assumption that the inner Lindblad resonance occurs where the CO abundance exhibits a sharp discontinuity, at a radius of 4 kpc.

Subject headings: galaxies: internal motions — galaxies: Milky Way — interstellar: molecules

I. INTRODUCTION

If the structure seen in spiral galaxies is due primarily to the passage of gas through a density wave, an important parameter to determine is the angular velocity of the spiral pattern about the center of the galaxy, $\Omega_p$. For our Galaxy, $\Omega_p$ is especially difficult to measure. Because we are located within the galactic plane, extinction vitiates optical measurements except in the near-vicinity of the Sun. Radio observations of $\text{H} \text{i}$ are potentially better, because they are much less affected by extinction. But they also determine this quantity imprecisely, because neutral hydrogen is so widely distributed in the Galaxy. It has been impossible even to state, with certainty, just what the grand design of our Galaxy is.

On the assumption that our galactic type is indeed a two-armed spiral, a number of techniques have been used to estimate $\Omega_p$ for our Galaxy, most of them reviewed recently by Nelson and Matsuda (1977). In general, these techniques include searches for the distances of large-scale radio features close to the galactic center, analysis of the migration of young stars in the solar neighborhood, and the comparison of actual line profiles of $\text{H} \text{i}$ emission with synthetic ones produced from a model of the Galaxy. The resulting determinations of $\Omega_p$ still supported by some astronomers range from $13.5 \text{ km s}^{-1} \text{kpc}^{-1}$ (Lin, Yuan, and Shu 1969) to $20 \text{ km s}^{-1} \text{kpc}^{-1}$ (Nelson and Matsuda 1977).

This paper presents an alternative method of determining the pattern speed, making use of direct observation of both conditions and kinematics in the inner Galaxy.

II. OBSERVATIONS

In our recent series of papers presenting observations of carbon monoxide within the galactic disk, W. B. Burton and I have derived a new rotation curve for the Galaxy which we have used to calculate the distribution of CO abundance as a function of galactocentric distance $R$ (Burton and Gordon 1977). This rotation curve is well-determined for $2 \text{kpc} < R < 10 \text{kpc}$, at least for northern hemisphere data, because it uses both recent high-quality $\text{H} \text{i}$ data and the narrow-line CO data. At $R > 4 \text{kpc}$ the new rotation curve is similar to the one given by Schmidt (1965). The distribution of CO with galactocentric radius is also well-determined. The discrete nature of the CO clouds makes our analysis essentially one of cloud counting, and we thereby avoid problems of interpreting radiation transfer. The generally symmetrical nature of galactic rotation makes it possible to assign a cloud to a galactocentric distance unambiguously, a welcome change from the problems of determining its distance from the Sun.

Our histogram of CO abundance with $R$, Figure 1, shows an abrupt discontinuity in the region $R = 4 \text{kpc}$. As described by Burton and Gordon (1977), the preparation of this histogram makes use of all our extensive observations of CO emission. The existence of this discontinuity is highly significant in terms of measurement uncertainties. It is not simply a result of an absence of gas with which to form molecules, because a similar histogram (Burton and Gordon 1977) shows $\text{H} \text{i}$ gas to be present at even smaller values of $R$.

III. ANALYSIS

The density-wave theory of galactic structure provides for compression of interstellar gas passing through the wave (see, for review, Roberts 1975). One can imagine that clouds form within this compression region, which leads ultimately to the presence of dust lanes and young stars slightly downwind of the wave. In this regard, the CO clouds may be tracers of the spiral density wave in our Galaxy.

It has been shown that the density waves cannot penetrate into the center of the Galaxy—specifically, through the ring known as the inner Lindblad resonance (ILR). Because the degree of compression increases toward the center of the Galaxy, we expect CO clouds to become increasingly abundant toward the galactic center up to the radius of the ILR, where compression and cloud formation should decrease...
rather abruptly. Thus the data in Figure 1 can be used to mark the radius of the ILR at 4 ± 0.25 kpc. We presume that the small amount of CO material lying just inside 4 kpc gets there by unknown transport mechanisms or by small asymmetries in galactic kinematics.

Using our newly derived rotation curve for the Galaxy, I calculated the variation of the epicyclic frequency of the gas $\kappa$ as a function of galactic radius. If we assume the Galaxy to have basically a two-armed structure, then we can calculate a curve for the inner resonance condition $\Omega - \kappa/2$ as a function of galactocentric radius. The ILR occurs at the radius where $\Omega_p = \Omega - \kappa/2$.

Figure 2 shows these calculations. The hatched region marks the position of the discontinuity in CO abundance. The intersection suggests that the pattern velocity of our Galaxy is $11.5 \pm 1.5$ km s$^{-1}$ kpc$^{-1}$. If the discontinuity in CO actually occurs slightly outside the ILR, then the data are quite consistent with the $\Omega_p$ of $13.5$ km s$^{-1}$ kpc$^{-1}$ given by Lin et al. Similar results obtain by using the kinematics given by Schmidt (1965), thereby suggesting that $\Omega - \kappa/2$ at $R \approx 4$ kpc is, in practice, not extremely sensitive to the precise rotation curve used.

IV. SUMMARY

The distribution of CO emission with galactocentric radius is consistent with a pattern speed of $11.5 \pm 1.5$ km s$^{-1}$ kpc$^{-1}$, if our Galaxy is a two-armed spiral. If other arms exist, then higher pattern speeds may also be compatible with our CO results.

With this value of $\Omega_p$, the outer Lindblad resonance
will occur at large distances from the galactic center, perhaps 24 kpc. The exact distance is difficult to calculate, because the rotation curve is poorly determined at $R > 10$ kpc. That CO clouds are not commonly found at such large distances should not be considered a problem. One can envision the existence of a threshold effect applying to the formation of molecular clouds, whereby compression has to exceed some critical value before clouds can be formed efficiently.

It is a pleasure to acknowledge conversations with W. Butler Burton, Alistair Nelson, and Frank Shu regarding these results.

REFERENCES
