CARBON MONOXIDE AND THE 3-KPC ARM FEATURE

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First isolated using the 21-cm HI spectral line, the 3-kpc arm exhibits the largest non-circular motion of any large-scale gaseous structure in the Galaxy (see e.g. Rougoor, 1964). Carbon monoxide observations best delineate the 3-kpc arm because the CO features are both narrower in velocity and also less confused with emission from more local gas than are HI observations. Because CO is a tracer of molecular hydrogen, the HI and CO data can in principle provide a good estimate of the total gaseous mass of the 3-kpc arm. A previous CO study of the inner Galaxy (Bania, 1977) suggested that, unless it is significantly tilted with respect to b=0°, the 3-kpc arm cannot be a continuous ring structure because emission at extreme positive velocities which should be produced by ring segments lying farther than 10 kpc from the Sun is absent. Consequently, the latitude distribution of CO in the 3-kpc arm has been studied by surveying ^{12}CO emission over the region $350° \leq \ell \leq 25°$ at b=0° and $\pm 0\overset{\circ}{.}33$. The survey positions are separated by $\Delta\ell = 1°$. This coarse angular sampling resolution is deemed sufficient because the typical 3-kpc arm CO cloud has a linear dimension of 100 pc (Bania, 1977). Such clouds will subtend $\sim 0\overset{\circ}{.}4$ at the maximum line-of-sight distances expected for the extreme positive velocity 3-kpc arm emission (~14 kpc).

CO emission from the 3-kpc arm feature is clearly seen in Figure 1 starting at $(\ell, v) = (-10°, -100$ km s$^{-1})$ and continuing until (~14°, ~20 km s^{-1}). In HI the feature is lost due to confusion with low velocity emission at $\ell \sim 6°$. The Figure 1 data are projected onto a common plane by sandwiching the b=0° line profile for each longitude with the $b = \pm 0\overset{\circ}{.}33$ profiles at that longitude. The resulting map will best show any continuity of the 3-kpc feature in (ℓ, v) space but unfortunately will mask any latitude structure. Examination of the individual latitude maps reveals that the 3-kpc arm CO emission is more evident, i.e. both more intense and more continuous, for $\ell < 0°$ at $b = 0\overset{\circ}{.}33$; for $\ell > 0°$ it is more evident at $b = -0\overset{\circ}{.}33$. Although suggestive of a tilt, these CO data are too scanty to make any definitive statement.

The average emission characteristics of a 3-kpc arm CO feature imply

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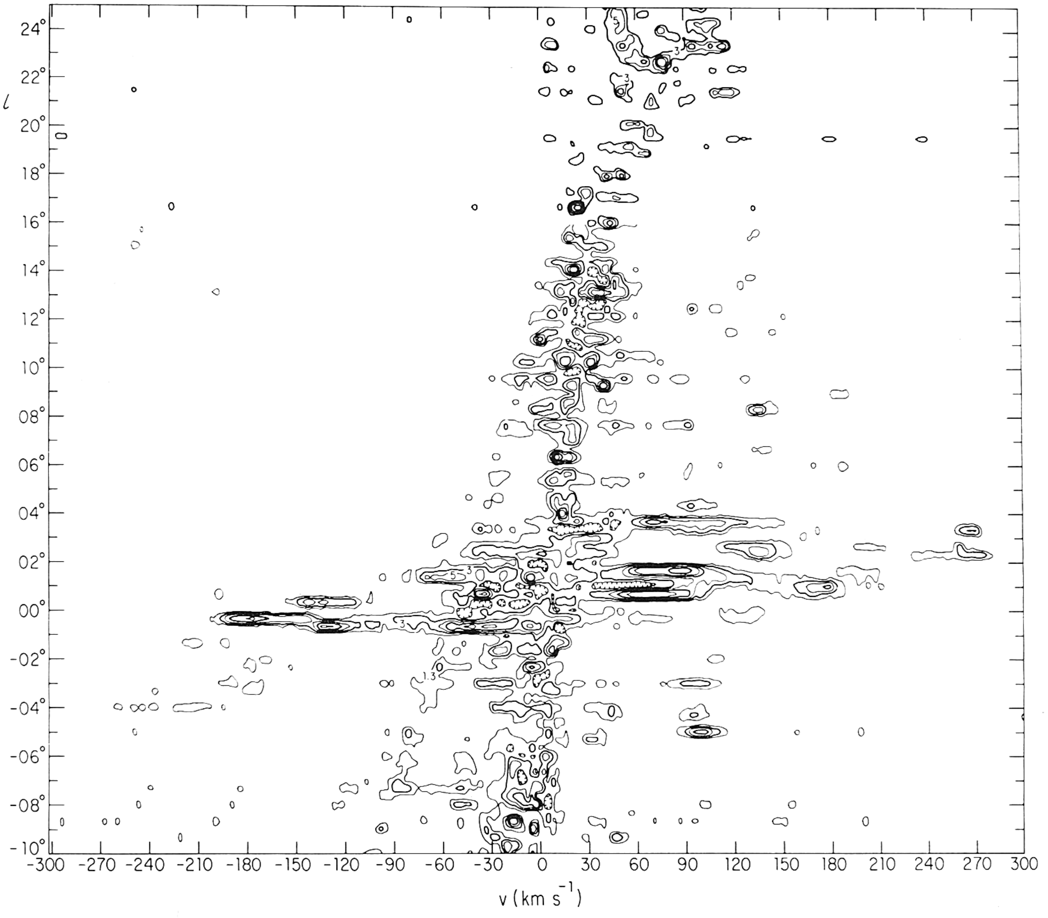

Figure 1: Longitude-velocity contour map of ^{12}CO emission for the region 350°≤ℓ≤25° and for latitudes b=0° and ±0°.33 (see text). The angular sampling resolution of the survey is Δℓ=1° and the LSR velocity resolution is Δv=2.6 km s^{-1}. Contours are drawn at T_A*= 1.3, 3, 5, 7.5, 10, 15, ... K. The lowest contour drawn is 3 times the mean rms noise level. The data quality for ℓ>16° was degraded by weather so for clarity the 1.3 K contour level has been suppressed in this region. The survey data were taken with the N.R.A.O. 11-m telescope on Kitt Peak. The N. R. A. O. is operated by Associated Universities, Inc., under contract with the National Science Foundation.

an H_2 column density of 2.4 x 10^{21} cm^{-2} using the methods given in Bania (1977). Assuming constant density spherical clouds and a 4 kpc radius for the arm, the observed angular size of the CO features, ~0°.8 implies an H_2 cloud mass of 4.7 x 10^5 $M_\odot$ and an H_2 mass of 2.4 x 10^7 $M_\odot$ for a 90° galactocentric arm segment. This is an upper limit because it assumes that the arm is comprised of an unbroken string of clouds. Even

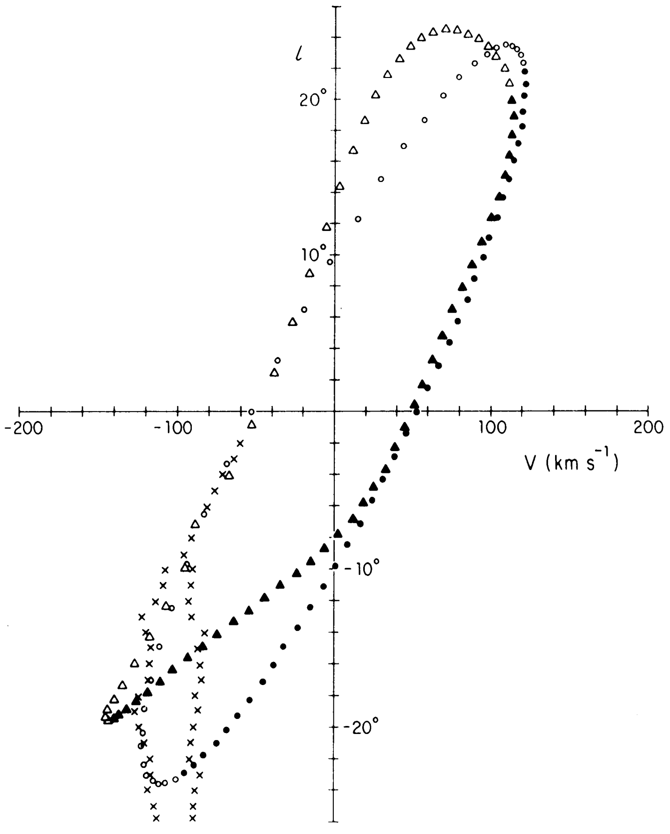

Figure 2: Longitude-velocity loci predicted by two kinematic models: circles show the simple kinematic ring of Cohen and Davies (1976) and triangles display the Simonson and Mader (1973) dispersion ring. Filled symbols represent positions lying farther than 10 kpc from the Sun. Crosses trace the HI emission maxima attributed to the 3-kpc arm. The HI data are from the DTM survey of Burke and Tuve (1963). Note that the observations do not show an obvious tangent point near $\ell \sim 334°-340°$.

so, the total HI mass, 3.6 x 10^7 $M_\odot$ (Cohen and Davies, 1976), still exceeds the H_2 mass. This arm segment has a total neutral hydrogen mass, M(HI) + M(H_2), of ~6 x 10^7 $M_\odot$ and an expansion energy, $\frac{1}{2}Mv^2$, of ~1.7 x 10^{54} ergs. If the HI and H_2 are uniformly mixed in clouds, the implies cloud mass is 10^6 $M_\odot$. Yet the total mass of the 3-kpc arm still appears to be too small to constrain the explosion models that have been invoked to produce the observed kinematics (van der Kruit, 1971, and Sanders and Prendergast, 1974).

The (ℓ,v) loci predicted by two simple kinematic models for the 3-kpc arm are shown in Figure 3. In each case, the plotted points were calculated for constant intervals in galactocentric azimuth. Thus any crowding in (ℓ,v) space is due solely to the coordinate transformation involved, and, for complete structures of constant density, enhanced emission would be expected in these regions. It is evident from a comparison of Figures 1 and 2 that while the models fit the data well for the region (ℓ,v)<(0,0), neither succeeds very well in predicting the CO emission locus anywhere else. In particular, the enhanced emission expected at extreme positive velocities for $\ell>0°$ is still not observed even though the $b=\pm0.^\circ33$ data sample a $|z|$ of ~80 pc at a distance of 14 kpc from the Sun. The HI 3-kpc arm has an observed z extent to half intensity of 90 pc (Cohen and Davies, 1976).

The simple kinematic ring model becomes a tangent to the line-of-sight at $\ell\sim23°$ where there in fact is an intense feature in the CO data. However, the counterpart southern tangent point is not present at $\ell\sim-23°$ as can be seen by the crosses in Figure 2 which trace the HI maxima in the survey of Burke and Tuve (1963). These authors point out that one cannot fit both the southern HI tangent point and the negative velocity (ℓ,v) slope of the 3-kpc arm feature simultaneously.

The CO and HI data suggest, therefore, that the 3-kpc arm is not a uniform circular feature, and in fact may not be at 3 kpc at all. It should be emphasized that we really only know that the 3-kpc arm lies somewhere between the Sun and Sgr A. Its "tangent points" do not occur at symmetric longitudes about $\ell=0°$ and in fact they lie dangerously close to regions in the (ℓ,v) diagram where pseudo-features are naturally produced by the observing geometry. Even a constant density, differentially rotating disk of optically thin gas could produce arcs of enhanced emission in these regions!

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DISCUSSION

de Vaucouleurs: From CO observations only, could you precisely define the longitude of the tangential point (or points) of the "Rougoor (3-kpc) arm"? Does it coincide with the HI tangential point?

Lockman: Can you be certain that the expanding arm is actually seen tangent to the line of sight at any longitude?

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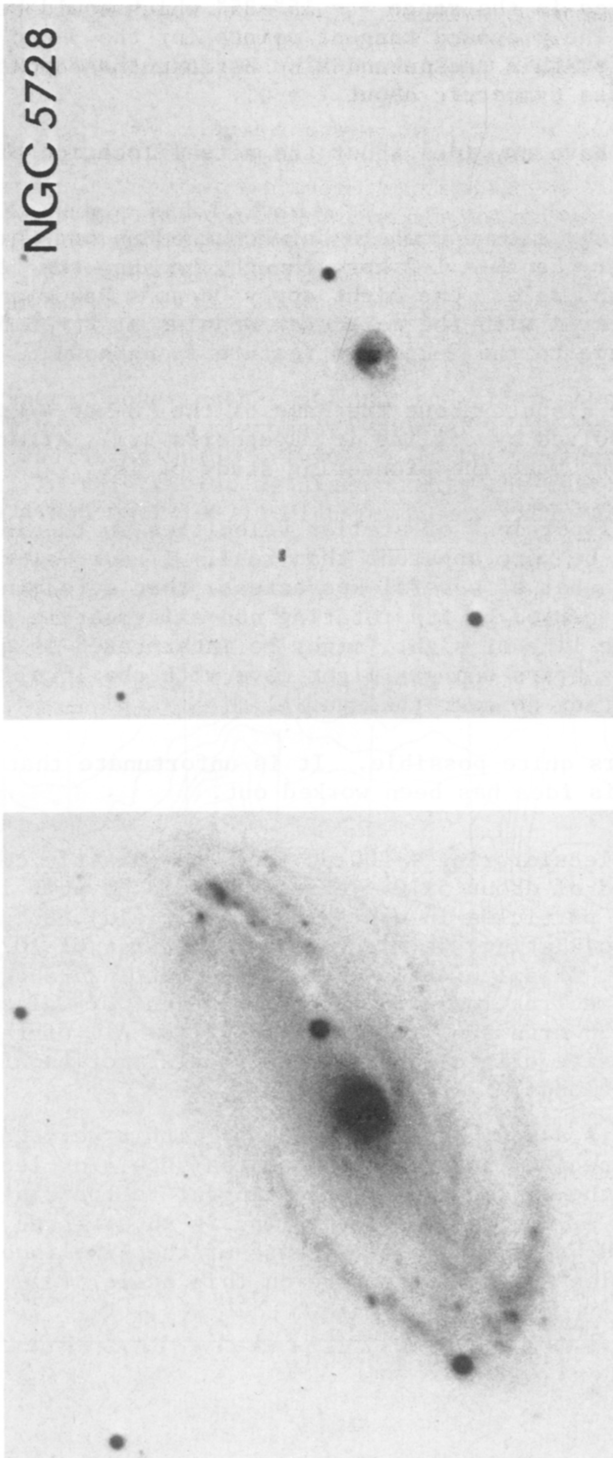

Figure caption: Reproductions of Las Campanas 2.5-m plates of NGC 5728, kindly made available by Sandage. Original scale 10″.8/mm; 103a-0 emulsion plus GG 385 filter. (left) exposure 45 min.; (right) exposure 5 min.

Bania: No. Pseudo features in the ℓ,v diagram produced by, for example, a constant density, differentially rotating disk of optically thin gas naturally form arcs in the range ℓ = 15°-25° which could be mistaken as tangent points. The proposed tangent points for the 3-kpc arm are not convincing both for this reason and also because these points do not occur at longitudes symmetric about ℓ = 0°.

Maihara: Do you have any idea about the actual location of the so-called 3-kpc arm?

Bania: It certainly lies somewhere between the Sun and Sgr A. It cannot be much closer than R = 1-2 kpc, though, because the feature subtends too large an angle. One might apply Occam's Razor and suggest that it is associated with the molecular annulus at R = 5.5 kpc. In short, the distance to the 3-kpc arm feature is unknown.

van Woerden: The dispute about the name of the "3- or 4-kpc expanding arm" could be resolved by calling it "Rougoor's arm", after our deceased young colleague who made the pioneering study of it.

Ostriker: The "dispersion" of stellar velocities in the interior part of the Galaxy may be more apparent than real. If our Galaxy has, as I consider likely, a bar of several kpc extent, then streaming motions along the bar (or caused by its rotating non-axisymmetric potential) projected onto the line of sight, might be interpreted as a dispersion. In fact, the young stars and gas might move with the local centroid in these regions as they do near the sun.

Oort: This appears quite possible. It is unfortunate that no proper model based on this idea has been worked out.

Sanders: The "molecular ring"--200 pc from the galactic center--has an oscillation period of about 5×10^6 years (or would have if its motion were just that of particles in a gravitational field). So to keep the molecular ring oscillating, we might require a burst of 10^{56} ergs every 5×10^6 years. Now, if all of this energy came out in a short time, say 10^5 years, and some fraction were radiation, then our Galaxy might be a Seyfert ($L \sim 10^{44}$ ergs s^{-1}) for 2% of the time. All of this, of course, presumes an explosive origin for the non-circular motion of the inner-Galaxy molecular clouds.

Rubin: NGC 5728 is a southern spiral galaxy with a very complex optical nuclear spectrum. Direct blue plates show a nuclear ring, radius ~7", with the nucleus apparently tangent to the ring. Adopting H = 50 km s^{-1} Mpc^{-1}, the radius of the ring is about 2 kpc. I thought these prints would be of interest, because of the likelihood that our Galaxy has a complex spatial structure on this scale.

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