### Table 1. Global Properties of NGC 4314

| Parameter / Note                                                                 | Value                      | Note |
|---------------------------------------------------------------------------------|----------------------------|------|
| Morphological Type                                                              | SBa                        | 1    |
| Environment                                                                     | Coma Sculptor Cloud        | 2    |
| Environment                                                                     | ~ 25 Galaxies              |      |
| Local Galaxy Density                                                            | 1.25 Gal/Mpc$^3$           | 2    |
| Optical center (J2000)                                                          |                            | 3    |
| RA                                                                               | 12$^h$ 22$^m$ 31$^s$. 98   |      |
| DEC                                                                             | +29$^\circ$. 53 44$'$. 2   |      |
| Optical center (B1950)                                                          |                            |      |
| RA                                                                               | 12$^h$ 20$^m$ 1. 88        |      |
| DEC                                                                             | 30$^\circ$.10 21 9         |      |
| $B_T$                                                                           | 11.43 ± .15               | 1    |
| $(B - V)_T$                                                                     | 0.85 ± .03                | 1    |
| Optical Size (Blue POSS print)                                                  | 4.6$'$ × 4.5$'$           | 4    |
| Optical Size (Red POSS print)                                                   | 4.6$'$ × 4.6$'$           | 4    |
| Position Angle (isophotal)                                                      | 59 ± 8$^\circ$             | 5    |
| Inclination                                                                     | 27$^\circ$ ± 4$^\circ$     | 6    |
| Systematic radial velocity                                                      | 978 km s$^{-1}$            | 2    |
| Adopted distance                                                                | 10 Mpc                     | 9    |
| Linear scale                                                                    | 48.5 pc arcsec$^{-1}$      |      |
| CO Luminosity                                                                   | $5.8 \times 10^7$ K km s$^{-1}$ pc$^2$ | 7    |
|                                                                                   | $4.6 \times 10^7$ K km s$^{-1}$ pc$^2$ | 8    |
|                                                                                   | $5 \times 10^7$ K km s$^{-1}$ pc$^2$ | 9    |
| 60 $\mu$mFlux Density                                                           | 3.71 Jy                    | 10   |
| 100 $\mu$mFlux Density                                                          | 7.3 Jy                     | 10   |
| H1 Mass                                                                         | $4.8 \times 10^6 M_\odot$  | 11   |
| Dynamical Mass                                                                  | $8.0 \times 10^{10} M_\odot$ | 11   |
| $L_{FIR}$                                                                       | $6.0 \times 10^8 L_\odot$  | 12   |
| Primary Bar                                                                     |                              |      |
| position angle                                                                  | 148$^\circ$                | 5    |
| length (radius)                                                                 | 66$''$                     | 5    |
| Nuclear Bar                                                                     |                              |      |
| position angle                                                                  | 150$^\circ$                | 3    |
| length (radius)                                                                 | 4$''$                      | 3    |

Notes to Table 1.
(1) RC3, (2) Tully 1989, (3) P2, (4) UGC, (5) P1, (6) Tully-Fisher, see Kenney et al. 1993, (7) Sage 1993b, (8) Combes et al. 1992, (9) G-B, (10) PSC, (11) Sage 1993, (12) Lonsdale et al. 1985.
| Parameter                           | Value                                      |
|------------------------------------|--------------------------------------------|
| Phase center                       |                                            |
| RA                                 | $12^{h} 22^{m} 31^{s}.90$ (J2000)           |
| DEC                                | $+29^\circ 53' 45''.4$                      |
| CO intensity peak                  |                                            |
| RA                                 | $12^{h} 22^{m} 32^{s}.14$ (J2000)           |
| DEC                                | $+29^\circ 53' 38''.4$                      |
| CO kinematic center                |                                            |
| RA                                 | $12^{h} 22^{m} 32^{s}.00$ (J2000)           |
| DEC                                | $+29^\circ 53' 42''.6$                      |
| Inclination                        | $21^\circ \pm 20^\circ$ (adopted)          |
| p.a. of line of nodes              | $115^\circ \pm 10^\circ$                   |
| Field of view (HPBW of primaries)  | $65''$                                     |
| Baselines                          | 4–77 k $\lambda$                           |
| Velocity of CO kinematic center (LSR) ($V_{sys}$) | $983 \pm 5$ km s$^{-1}$                   |
| Velocity resolution                | 13 km s$^{-1}$                             |
| **Map-specific Parameters**        |                                            |
| Weighting used to make maps        |                                            |
| Uniform                            | $2''29 \times 2''17$                       |
| Natural                            | $3''12 \times 2''7$                        |
| Linear size of synthesized beam    | $111 \times 105$                           |
| Beam Area                          | 5.63                                       |
| Position angle of synthesized beam | $-16.6$                                    |
| RMS noise in channel maps          | $0.028$                                    |
| Equivalent TB for 1 Jy beam$^{-1}$ | 19.4                                       |
| Peak Brightness Temperature ($T_B$)| 4.9                                        |
| Interferometer flux                | 245 Jy km s$^{-1}$                         |
| CO flux ($r < 8''$)                | 190 Jy km s$^{-1}$                         |
| L(CO) ($r < 8''$)                  | $4.7 \times 10^7$ K km s$^{-1}$pc$^{-2}$   |
| Mass of molecular gas ($r < 8''$)  | $2.1 \times 10^8 M_\odot$                 |
|                                    |                                            |
NGC 4314. III. Inflowing Molecular Gas Feeding
a Nuclear Ring of Star Formation

G. Fritz Benedict
McDonald Observatory, University of Texas, Austin, TX 78712

Beverly J. Smith
IPAC, California Institute of Technology, Pasadena, CA 91125

and

Jeffrey D. P. Kenney
Astronomy Dept., P.O. Box 208101, Yale University, New Haven, CT 06520

Received __________________; accepted ________________

1Based on observations collected at the Owens Valley Radio Observatory
NGC 4314 is an early-type barred galaxy containing a nuclear ring of recent star formation. We present CO(1-0) interferometer data of the bar and circumnuclear region with 2.3″ × 2.2″ spatial resolution and 13 km s⁻¹ velocity resolution acquired at the Owens Valley Radio Observatory. These data reveal a clumpy circumnuclear ring of molecular gas. We also find a peak of CO inside the ring within 2″ of the optical center that is not associated with massive star formation. We construct a rotation curve from these CO kinematic data and the mass model of Combes et al. (1992). Using this rotation curve, we have identified the location of orbital resonances in the galaxy. Assuming that the bar ends at corotation, the circumnuclear ring of star formation lies between two Inner Lindblad Resonances, while the nuclear stellar bar ends near the IILR. Deviations from circular motion are detected just beyond the CO and Hα ring, where the dust lanes along the leading edge of the bar intersect the nuclear ring. These non-circular motions along the minor axis correspond to radially inward streaming motions at speeds of 20 – 90 km s⁻¹ and clearly show inflowing gas feeding an ILR ring. There are bright H II regions near the ends of this inflow region, perhaps indicating triggering of star formation by the inflow.
1. Introduction

Inner Lindblad resonances (ILRs) are thought to strongly influence gas motions and star formation in the central regions of galaxies. Gas surface densities often peak near the ILR (Combes et al. 1992; Kenney et al. 1992), lending support to the idea that the inward flow of gas along galaxian bars slows down and piles up between the OILR and the IILR (Combes 1988; Shlosman et al. 1989). Studies of the CO (1-0) distribution within the central regions of barred spirals (Kenney et al. 1992; Kenney 1995; Regan, Vogel, & Teuben 1995; Rand 1995; Sakamoto et al. 1995) show a variety of molecular gas morphologies near the ILR, including rings, spiral arms, and “twin peaks” with two maxima where the dust lanes along the primary bar cross the ILR. In the case of the starburst galaxy NGC 3504, the CO peaks near the nucleus, probably inside the ILR (Kenney et al. 1993). The dynamical and evolutionary differences responsible for this variety are not yet understood, but are critical for understanding starbursts and the formation and evolution of compact circumnuclear stellar disks (Kormendy 1993) and stellar bulges (Pfenniger & Norman 1990).

At present, only a handful of barred spirals have been mapped in CO at sufficient resolution to study the effects of ILRs on the gas distribution and kinematics. The barred spiral galaxy NGC 4314 is a particularly good galaxy to study because it exhibits evidence for many features associated with resonances and it is nearly face-on ($i \sim 23^\circ$). It has a large-scale stellar bar of diameter 130″ (6.3 kpc) and a prominent circumnuclear ring of star formation of diameter 10″ (500 pc) that is visible in Hα (Pogge 1989), radio continuum (Garcia-Barreto et al. 1991; hereafter G-B), and optical color maps (Benedict et al. 1992; hereafter P1). CO (1-0) mapping of NGC 4314 (Combes et al. 1992) at 5″ resolution revealed the presence of a molecular ring slightly smaller than that of the ring of star formation. Outside of these rings, a blue elliptical feature of diameter 20-25″ (1 kpc) is seen in optical color maps, which may correspond to a ring of relatively young but non-ionizing
stars (P1). This feature, which can be seen on the unsharp masked optical image shown in Fig. 1 (from P1), is elongated perpendicular to the primary bar, suggesting that it extends outward to the IILR. Combes et al. (1992) suggest that in this galaxy star formation is propagating inwards. This is in contrast with the evolutionary scenario proposed by Kenney et al. (1993) for strong starbursts, in which star formation devours gas most rapidly in the center, ultimately forming a ring of gas near the ILR.

Inside the H\textsc{ii} region ring, a nuclear stellar bar of diameter 8" (400 pc) is seen in \textit{Hubble Space Telescope} (HST) I band data (Benedict et al. 1993; hereafter P2). This nuclear bar is aligned parallel with the large scale bar, which suggests that the nuclear bar has the same pattern speed as the primary bar, and lies within the IILR (Binney & Tremaine 1987).

In this paper, we present new CO (1-0) maps of NGC 4314, obtained at twice the spatial resolution as the Combes et al. (1992) data. The observations are described in Section 2, while the CO distribution and kinematics are discussed in Sections 3 and 4, respectively. In Section 5 we compare NGC 4314 with other galaxies and discuss star formation in this galaxy. Some general properties of NGC 4314 are tabulated in Table 1.

2. Observations

We observed NGC 4314 in the CO (1-0) line using the Owens Valley Radio Observatory (OVRO) millimeter-wave interferometer (Padin et al. 1991) in five configurations between April and June 1991. Projected baselines ranged in length from 10 to 200 meters. At that time OVRO consisted of a three element array with 10.4m dishes (HPBW = 65" and SIS receivers. The 325 MHz receivers give 13 km s\(^{-1}\) resolution and an instantaneous bandpass of 416 km s\(^{-1}\). The quasar 1219 + 285 was used for phase calibration, Uranus and Neptune for flux calibration.
After calibration, channel maps were made with both uniform and natural weightings using AIPS. Uniform weighting produces higher resolution maps, with less sensitivity, while natural weighting provides greater sensitivity with less resolution. The latter reduction mode provides higher signal to noise information on the regions in the primary bar of NGC 4314 containing fainter CO intensity.

All maps were made as $256 \times 256$ arrays with $0.5''$ pixel$^{-1}$. Natural weighting produced a resolution of $3.1 \times 2.7''$ with channel noise $0.022$ Jy beam$^{-1}$. These maps were CLEANed to a $0.045$ Jy beam$^{-1}$ level. Using uniform weighting, we obtained a $2.3 \times 2.2''$ beam with channel noise $0.028$ Jy beam$^{-1}$, CLEANed to a $0.07$ Jy beam$^{-1}$ level. For both weightings we have made primary beam corrections. Fig. 2 presents our uniformly weighted channel maps. These maps have absolute positional accuracy of about $0.5''$. Table 2 summarizes the interferometer-related parameters.

The total CO flux observed by OVRO is $245$ Jy km s$^{-1}$ (Table 2), while the CO luminosity is $4.7 \times 10^7$ K km s$^{-1}$ pc$^2$. This luminosity is consistent with the single dish observations of G-B and with the Nobeyama Millimeter Array results of Combes et al. (1992) (see Table 1). Therefore we have recovered essentially all of the CO flux from this galaxy with our OVRO observations.

3. Morphological Results

3.1. CO Morphology

Uniformly weighted and naturally weighted total intensity maps were constructed using the AIPS moment routines. Fig. 3 presents the uniformly weighted CO intensity map. The strongest CO emission arises from an incomplete, clumpy ring with an off-center minimum.
There are five clumps of emission along the ring, separated by gaps. The largest of these gaps is at p.a. = 239°. A secondary gap occurs at p.a. = 330°. In addition to the clumps in the ring, we find strong CO emission within 2″ of the optical center.

Two symmetrically located features along p.a. ~20° extend out from the ring. These are associated with the dust lanes that lie along the leading edge of the primary stellar bar. These lanes are detected in CO as they curve around to intersect the nuclear ring. We refer to these features as inflow spurs, since the CO velocity field shows clear evidence for inflow motions here (§4.2).

Fig. 4 shows the naturally weighted CO intensity distribution, covering about 4 times the area on the sky as Fig. 3. Note the CO clumps extending on either side out from the ring along p.a. ~148°. These extensions lie along the leading edge of the primary stellar bar (P1).

3.2. Comparison of CO to Optical and Radio Continuum

3.2.1. Maps

In Fig. 5a we overlay the uniform-weight CO map contours on the optical unsharp masked image shown in Fig. 1. The dust and CO are relatively coincident for the CO arcs to the SE and NW, while the dust lanes lie outside the CO ring to the NE and SW. Along the primary bar, a dusty area is seen to the SE (see Fig. 1), a region called the ‘dust bowl’ in P1. A comparison of optical and CO intensity from the naturally-weighted data for a larger area of the galaxy (Fig. 5b) shows weak (∼ 3σ) CO sources coincident with the dust bowl. Note in both Fig. 5a and 5b the anticoincidence of CO with the outer ellipse of relatively young stars.
In Fig. 6 the Pogge (1989) Hα + [N II] map is overlaid on a uniform weight CO intensity contour plot. The Wakamatsu & Nishida (1980) Hα-bright knots A (p.a. ~ 90°) and B (p.a. ~ 178°) are the second and third strongest Hα sources in the Pogge map. The Hα peaks tend to lie outside of the CO ring (see also the profiles in Fig. 7 - 9). At the largest CO gap, Hα is also weak.

The Hα + [N II] map resembles the 6 cm radio continuum map shown in G-B and our observations confirm the results of Combes et al. (1992) that the ring of star formation has a larger radius than the molecular ring.

3.2.2. Profiles

The profiles in Fig. 7 - 10 offer a more detailed and quantitative comparison between the distributions of CO intensity, blue light (μB, P1), μ(Hα+[N II]) (uncalibrated Hα+[N II] surface intensity, Pogge 1989), μI−J and μB−H (respectively identified as the best tracer of dust and of new stars in P1). Fig. 7, 8, and 9 are primary bar major axis, primary bar minor axis, and E-W cuts across the galaxy, respectively. Fig. 10 shows a cut through the dust bowl, perpendicular to the primary bar. For these plots the uniformly-weighted CO intensity has been converted to σH2(M⊙ pc−2) assuming (Bloeman et al. 1986, Kenney et al. 1992)

\[ \sigma_{H_2}(M_\odot pc^{-2}) = 470 I_{CO} (Jy \text{ km s}^{-1}\text{arcsec}^{-2}) \]

Hα is a tracer of the local star formation rate (SFR). These plots also contain the log of the ratio of (Hα+[N II])/CO. In H II regions, where the observed Hα+[N II] emission is dominated by Hα and the ionization is due to OB stars, this ratio is proportional to the gas depletion timescale, or Star Formation Efficiency.
In Fig. 7, the dust lanes at $r = \pm 5''5$, seen as reddening in the $\mu_{I-J}$ profile, are very prominent in CO. There is also considerable CO emission near the nucleus; Fig. 7, 8, and 9 show the CO surface density near the nucleus as high as in the ring of star formation. The $\mu_{(H_\alpha+[N II])}$ profiles corroborate that the H II regions in the ring lie slightly outside the CO ring. Dips in the $\mu_{B-H}$ profile are coincident with the new stars at the H$\alpha$ ring, $r = \pm 7''$. The $(H\alpha+[N II])/CO$ ratio shows a relatively higher SFE near the nuclear ring, especially to the NW.

There is also a secondary source in $\mu_{(H_\alpha+[N II])}$, peaking $\sim 1''$ S of the center. This is likely due to strong [N II] emission contaminating the H$\alpha$+[N II] image near the center. Keel (1983) identified NGC 4314 as having an “[N II]”-type optical spectrum. Measured values of [N II]/H$\alpha$ for the NGC 4314 nucleus range between 1 and 2.5 (Keel 1983; Wakamatsu & Nishida 1980; Stauffer 1982; Smith et al. 1987) and Keel (1983) identified NGC 4314 as an “[N II]”-type galaxy. The ratios of H$\alpha$, H$\beta$, [N II] $\lambda 6584$, [O III] $\lambda 5007$, and [O I] $\lambda 6300$ given in Smith et al. (1987) are consistent with the LINER definition given in Heckman (1980) & Dahari (1985). Therefore the nuclear peaks in H$\alpha$+[N II] and (H$\alpha$+[N II])/CO may not be due to star formation.

Note the coincidence of an increase in $\mu_{I-J}$ profile, a decrease in $\mu_B$, and a peak in the $\sigma_{H_2}$ profile to the SE. These all argue that CO and dust are associated. How good is this correlation? Is there CO only where there is dust? The peak in the $\sigma_{H_2}$ profile to the SE (Fig. 7) is well-described by a gaussian centered at $r = -5''4$, with FWHM = 4''.14. From the HST $\mu_1$ data presented in P2, we find the dust lane can also be described by a gaussian centered at $r = -5''5$, with FWHM = 1''.60. Along this p.a. the OVRO synthesized beam can be considered to be a gaussian with FWHM = 2''.20. Convolving the OVRO beam with the dust profile produces a distribution with FWHM = 2''.70. Evidently, the CO is not confined to the dust lane, but spills over in a symmetric distribution. We next deconvolve
the OVRO beam from the Fig. 7 \( \sigma_{\text{H}_2} \) profile and determine that the actual CO distribution has FWHM = 3\arcsec 51 and a peak \( \sigma_{\text{H}_2} = 2550 \, M_\odot \, \text{pc}^{-2} \) at the dust lane center.

Along a slice perpendicular to the primary stellar bar (Fig. 8), we again find strong CO near the nucleus and near the dust lanes associated with the ring. (H\(\alpha\)+[N II]) peaks outside the CO to the NE, but inside to the SW. The (H\(\alpha\)+[N II])/CO ratio picks up near \( r = -4'' \) at a gap in the CO ring. There is an increase in the SFR at \( r = -1'' \), due to the observed CO deficiency, or to [N II] contamination from the LINER phenomenon. To the SW, the redder dust lane at \( r = 6'' \) is present in CO as well. The CO maximum at \( r \sim 4''5 \) to the NE is not as pronounced in the color indices as that to the SW, to be expected if the SW side of the galaxy is nearer.

For completeness we provide a set of profiles (Fig. 9) passing East-West through knot A, the second most intense H\(\text{II} \) region seen in the Pogge (1989) data. The dust to CO correlation is not as striking, primarily because dust signatures are weak in \( \mu_\text{I-J} \) and \( \mu_\text{B-H} \).

There is one other location where comparisons with optical data might prove useful; at the “dust bowl” in the primary stellar bar to the SE at \( r \sim 23'' \). In Fig. 10 we plot profiles passing through the dust bowl, perpendicular to the primary stellar bar. The profiles are \( \mu_\text{B}, \mu_\text{V-I}, \) and \( \mu_\text{B-V} \) (P1) along with \( \sigma_{\text{H}_2} \) derived from the natural weight map (Fig. 3). Again, dust and CO are well correlated, with reddening in \( \mu_{\text{V-I}} \) matching increases in \( \sigma_{\text{H}_2} \) all along the profile.

We test the reality of this dust and CO correlation in Fig. 11, showing the relationship between the measured CO intensity and \( A_\text{V} \) across the dust bowl in the range \( 1 \leq \times \leq 7'' \). The \( A_\text{V} \) values were derived in P1 from B-V surface color indices. The correlation demonstrates the quality of the CO data at the dust bowl location. This suggests that most of the weak CO features detected along the primary stellar bar (Fig. 3) are probably real.
As a final check of the reality of this feature in CO, we derive an $N_p$ to $A_V$ relationship. From Fig. 11 we determine

$$I_{CO}(\text{Jy arcsec}^{-2} \text{ km s}^{-1}) = a + b A_V \text{ (mag)}$$

where $a = 0.080 \pm 0.023$ and $b = 1.955 \pm 0.178$. Converting the slope to K km s$^{-1}$, using (Table 2) 1 Jy arcsec$^{-2} = 1.19$ K, we find a slope of 2.54 K km s$^{-1}$ mag$^{-1}$. From Bloemen et al. (1986)

$$N(H_2)(\text{cm}^{-2}) = 2.8 \times 10^{20} I_{CO} \text{ (K km s}^{-1})$$

Hence,

$$N(H_2) = 7.1 \times 10^{20} A_V$$

and, introducing a factor of two in converting from $H_2$ to $N_p$,

$$N_p = 1.4 \times 10^{21} A_V$$

in general agreement with a value

$$N_p = 1.8 \times 10^{21} A_V$$

derived from Savage & Mathis (1979), assuming $A_V/E(B-V)= 3.1$. The agreement suggests that, at least in this part of NGC 4314, a dust screen description is valid (Witt et al. 1992).

Unfortunately, as discussed in P1, the dust bowl is the only region in NGC 4314 for which we can obtain reasonable values for $A_V$. This is possible only by exploiting the symmetry and the relatively uniform stellar population of the primary stellar bar. In the more complex circumnuclear region, B-V color variations are due to spatial variations in the stellar populations, as well as dust extinction.

4. Kinematical Results
4.1. The CO Velocity Field and the Rotation Curve

In Fig. 12 we show the naturally weighted velocity field, which is consistent with predominately circular motion for \( r < 10'' \). From these data, we have determined the systemic velocity \( V_{\text{sys}} \), the dynamical center of the galaxy \((\alpha, \delta)\), the position angle of the line of nodes \( \phi \), the inclination \( i \), and a rotation curve \( V(R) \). We used the iterative technique of Puche, Carignan, and Wainscoat (1991), which employs a tilted ring model. Our data was binned into seven rings, each 1.5'' in width. Velocity values within each ring were weighted by the cosine of the azimuthal angle (relative to the line of nodes) in the plane of the galaxy. We first held \( \phi \) and \( i \) constant and fit for \( \alpha, \delta, \) and \( V_{\text{sys}} \). Next, we held \( \alpha, \delta, \) and \( V_{\text{sys}} \) constant and fit for \( \phi, i, \) and \( V(r) \), fitting the receding and approaching halves of the velocity field separately. We included only data within 45° of the major axis. Our results are listed in Table 2.

The inclination derived from this analysis \((21° \pm 20°)\) is quite uncertain due to the nearly face-on orientation of NGC 4314, however it is consistent with the value found in P1 \((23° \pm 8°)\), assuming that the outer isophotes obtained from digitally stacking the POSS O and E plates are intrinsically circular. However, the outer isophotes may be intrinsically oval, since outer rings and pseudorings located at the OLR are generally elongated (Buta 1993). An argument based on the Tully-Fisher relationship (see Kenney et al. 1993) gives \( 27° \pm 4° \). We choose \( i = 21° \) to determine the CO-derived rotation curve.

In an effort to extend the rotation curve outward from the OVRO limit, we have adopted the rotation curve of Combes et al. (1992) for \( r > 10'' \). This curve is obtained from a mass model of the galaxy based on a K-band image, which presumably accurately traces the stellar mass in the galaxy. We choose the Combes model derived rotation curve over that from Quillen et al. (1994), since the agreement with the CO velocities in the center of the galaxy is better.
Fig. 13a shows our OVRO and the Combes et al. (1992) rotation curves. Agreement between the two rotation curves is good for $r \leq 7''$. The CO curve flattens at $r = 7''$ with $V_{\text{max}} \sim 175$ km s$^{-1}$. Assuming that the ring is co-planar with the plane of the galaxy, has a radius of $6''7$, and a circular velocity of $175$ km s$^{-1}$, the period of rotation for the gas in the ring is $11$ My.

4.2. Deviations from Circular Velocity

Deviations from circular velocity can be seen directly on the velocity map shown in Fig. 12. There are regions associated with the dust lanes just outside the nuclear ring (e.g., Fig. 5) where the isovelocity contours bend sharply by $\sim 90^\circ$. To study these regions in more detail, we obtain a velocity residual map by producing a model galaxy velocity field from the rotation curve, Fig. 13a, and subtracting it from the observed CO velocity field. This is shown in Fig. 14, overlaid on the CO intensity map.

This comparison shows that the largest deviations from circular motion occur in two symmetrically located spurs, just outside the ring and near where the dust lanes merge with the ring. These spurs are located along the minor axis, where, within a disk, non-circular motions imply radial motions. If the dust lanes are truly along the leading edge of the bar, and the spiral arms are trailing, then the southwest side of the galaxy is closest to us and these radial deviations imply inflow. These local inflow speeds reach their maximum of 90 km s$^{-1}$ at $r \sim 10''$ and gradually decrease as the nuclear ring is approached and crossed. Inflow along the leading edge of a bar is predicted by theory and models (e.g., Roberts et al. 1979, Athanassoula 1992b) but is rarely seen as clearly as it is in NGC 4314.

We can estimate the mass inflow rate into the ring. The CO flux in the two inflow spurs ($\pm 7''$ from the nucleus) is 50 Jy km s$^{-1}$, which corresponds to a gas mass of $M(H_2 +$
$\text{He}) = 7 \times 10^7 \, M_\odot$. Adopting a mean inflow speed of $30 \, \text{km s}^{-1}$ implies that the gas now at $7''$ will reach the nucleus in $336 \, \text{pc}/30 \, \text{km s}^{-1} = 10^7 \, \text{yr}$. Thus the average inflow rate over this time is $7 \times 10^7 \, M_\odot/10^7 \, \text{yr} = 7 \, M_\odot \, \text{yr}^{-1}$.

Strictly speaking, the inflow speeds measured in Figure 14 are local streaming motions, and do not necessarily represent net inflow speeds. Gas along bars has the largest inward motion where it piles up and is easiest to detect, but is predicted to move outwards on other parts of its orbit, where the gas surface density is lower (Athanassoula 1992a). This is a greater concern far out along bars than just outside the ILR ring, and we believe that the net inflow speeds are close to the local streaming motions in this part of NGC 4314.

From the thermal radio continuum flux, G-B estimate an extinction-corrected H$\alpha$ flux for NGC 4314 of $1.5 \times 10^{-12} \, \text{erg s}^{-1} \, \text{cm}^{-2}$, which corresponds to a star formation rate of $0.16 \, M_\odot \, \text{yr}^{-1}$, using an extended Miller-Scalo IMF as in Kennicutt (1983). Since this rate is much lower than the inflow rate, the gas mass in the ring may be increasing with time. And, since little CO is seen in the dust lanes, this process cannot continue much longer.

In Fig. 15b the velocity deviation map is compared to the Pogge (1989) H$\alpha$ image. Luminous H$\Pi$ complexes are located within $1''$ of the terminus of each inflow spur. This suggests that gas flowing inward along the bar collides with gas already in the ring, triggering star formation. The H$\Pi$ regions appear upstream from the inflow zones, suggesting that it is gas already in the ring that is involved with star formation. These regions may be similar to the bar end in M83, where two gas streams meet and one of them undergoes star formation (Kenney & Lord 1991).

The existence of CO near the nucleus implies the need for a collection mechanism. In P2 we presented evidence for the existence of an $8''$ long nuclear bar, oriented parallel to the primary stellar bar. If this nuclear bar is a real bar-like dynamical feature, then gas flow patterns of the type thought to be associated with bars should be present. Fig. 16 shows
that deviations from circular motion (the same differential velocities presented in Fig. 14, but with $\Delta V = 5 \text{ km s}^{-1}$) are seen along the nuclear bar. However, the velocity pattern is not everywhere consistent with the streaming motions generally associated with bars. The signal-to-noise ratio in this central region, where CO emission is weak, may be too low to show the streaming motions clearly.

4.3. Resonances

From the rotation curve in Fig. 13a, we produce standard resonance curves (c.f. Devereux et al. 1992), and plot them in Fig. 13b. Because the angular velocity of this bar is unknown, we assume a pattern speed of $\Omega_p = 3.5 \text{ km s}^{-1} \text{ arcsec}^{-1}$, which places corotation at the end of the primary bar. A $\mu_{B-I}$ map of NGC 4314 (Fig. 16) shows that it has an outer elliptical distribution of newer stars with $r = 13''$ oriented perpendicular to the primary stellar bar (P1). NGC 4314 also has a nuclear bar with a 4'' radius (P2) oriented parallel to the primary stellar bar. These orthogonal structures suggest nested resonances (Combes 1988). The resonance curves in Fig. 13b would predict OILR at $r = 13$ and IILR at $r = 4''$ for a bar pattern speed $\Omega_p = 3.5 \text{ km s}^{-1} \text{ arcsec}^{-1}$, corresponding to 72 km s$^{-1}$ kpc$^{-1}$. This places the outer Lindblad resonance (OLR) at $r \sim 98''$, coincident with the elliptical outer isophotes discussed in P1. These elliptical isophotes have their major axis oriented perpendicular to the primary stellar bar, as do some rings and pseudo-rings in other galaxies that are located at the OLR (Buta & Crocker 1993).

5. Comparisons with other Galaxies
A concise review placing NGC 4314 in the context of other barred galaxies with similar observations can be found in Kenney (1995). Here we offer a few specific comparisons. In the central regions of M101 (Kenney et al. 1992), NGC 6951 (Kenney et al. 1992), NGC 1530 (Regan, Vogel, & Teuben 1995), and M100 (Rand 1995; Sakamoto et al. 1995), CO maps show spiral-shaped features extending out from a circumnuclear ring or partial ring of HII regions. In many of these examples the CO is strongest at the intersection of the ring with the dust lanes along the leading edge of the bar. This morphology is particularly striking in NGC 3351, where the CO is concentrated into “twin peaks” located symmetrically about the nucleus oriented perpendicular to the large-scale bar (Kenney et al. 1992). These peaks have been interpreted as regions of orbit crowding, where inflowing gas from the bar meets gas on more circular orbits near the ILR (Kenney et al. 1992).

Our data for NGC 4314 show spiral-shaped inflow spurs, but they are weaker than in most of these other galaxies. NGC 4314 also does not have a “twin peak” morphology. There are modest CO peaks located where the inflow spurs meet the ring, but the strongest CO peaks are located elsewhere in the ring. The variety in gas morphology between galaxies is probably due in part to dynamical differences, including variations in the degree of central concentration and the strength of the bar. The rotation curve and the pattern speed of the stellar bar determine the number, location, and separation of the ILRs. Gas behavior also depends on whether there are small scale nuclear bars (Shlosman et al. 1989; Wozniak et al. 1995), and the relative position angles of the bars, if they are independently rotating. Some of the variety may also be due to evolutionary differences. Timescales are relatively short in circumnuclear regions; starburst timescales are \( \sim 10^7 - 10^8 \) yr, and dynamical timescales are \( \sim 10^7 \) yr. The relative weakness of the CO in the inflow spurs of NGC 4314 compared to these other galaxies may mean that in NGC 4314 the gas in these dust lanes has already been driven into the center. The observation that the molecular gas in NGC 4314 lies inside the star forming ring lead Combes et al. (1992) to suggest that the ring is shrinking.
with time due to dynamical friction from the bulge stars. As noted previously, there is an elliptical distribution of newer, but non-ionizing stars outside of the ring of H\textsc{ii} regions (P1). There is a color progression along this ellipse, such that stars closer to the ring are bluer (P1). Since our OVRO data show very little CO along this ellipse, we conclude that this color variation is due to age rather than extinction. Therefore, younger stars are found closer to the H\textsc{ii} region ring, supporting the idea of a shrinking ring of star formation.

This observation, along with the observation that essentially all of the molecular gas in the galaxy is found in or inside the ring and the fact that NGC 4314 is extremely deficient in atomic gas (G-B), lead Combes et al. (1992) to hypothesize that NGC 4314 is in a late stage of evolution, and that accretion to the NGC 4314 ring has stopped. Our observations show that inflow is in fact still occurring. However, since little CO is seen in the dust lanes, this process cannot continue much longer.

6. Summary

The major observational results of this paper include

1. We confirm the ring-like CO morphology first reported by Combes et al. (1992).

2. We discover significant CO near the center of NGC 4314 without associated recent star formation.

3. CO associated with dust along the leading edge of the primary stellar bar is detected at a 3-\(\sigma\) level. This association is confirmed for the dust bowl region by a strong correlation of CO intensity with extinction estimated from optical color maps.

4. Much of the CO in and near the ring is coincident with dust.
5. We identify the nested, orthogonal resonances in NGC 4314. We identify the IILR with the end of the nuclear bar, OILR with the outer extent of an elliptical distribution of less recent star formation, corotation near the end of the large-scale bar, and the OLR with the elliptical outer isophotes oriented perpendicular to the bar. The strongest star formation occurs between the IILR and OILR and closer to the IILR.

6. A color gradient, from blue near the IILR to red near the OILR, is likely due to stellar age differences, not reddening. CO emission is strong near the IILR and weak near the OILR, hence the expected reddening gradient is the opposite of the observed color gradient.

7. Radial inflow at speeds of 20-90 km s$^{-1}$ is detected in two spurs of molecular gas located just outside the star-forming ring. Significant H$\alpha$ emission occurs where the inflow spurs meet the ring.

Benedict thanks Jeff Achtermann, Antonio Garcia-Barreto, Jim Higdon, and Hong Bae Ann for useful discussions. Melody Brayton provided invaluable assistance with LaTex. We thank Rick Pogge for providing an H$\alpha$ map of NGC 4314. Benedict acknowledges support from NASA grant NAG5-1603. B. J. Smith acknowledges support from NASA grant NAG2-67.
REFERENCES

Athanassoula, E. 1988, in *Proc. Joint Varenna-Abastumani International School and Workshop on Plasma Astrophysics*, ESA SP-285, Vol. 1, 341

___________ 1992a, MNRAS, 259, 328

___________ 1992b, MNRAS, 259, 345

Benedict, G. F., Higdon, J. L., Tollestrup, E. V., Hahn, J., & Harvey, P. M. 1992, AJ, 103, 757 (P1)

Benedict, G. F., Higdon, J. L., et al. 1993. Astron. J., 105, 1369 (P2)

Binney, J. and Tremaine, S. 1987, *Galactic Dynamics*, (Princeton: Princeton Univ. Press)

Bloemen et al. 1986, A&A, 154, 25

Buta, R. J. 1993, PASP, 105, 654

Buta, R. J. & Crocker, D. A. 1993, AJ, 105, 1344

Combes, F., 1988, in *Galactic & Extragalactic Star Formation*, ed. by E. Pudritz & M. Ficks, Kluwer, Dordrecht, 475

Combes, F., Gerin, A., Nakai, N., Kawabe, R. & Shaw, M. A. 1992, A&A, 259, 1, L27

Dahari, O. 1985, ApJS, 57, 643

Devereux, N. A., Kenney, J. D. P., & Young, J. S. 1992, AJ, 103, 784

Garcia-Barreto, J. A., Downes, D., Combes, F., Gerin, M., Magri, C., Carrasco, L., & Cruz-Gonzalez, I. 1991, A&A, 244, 257 (G-B)

Heckman, T. M. 1980, A&A, 87, 152

Keel, W. 1983, ApJS, 52, 229

Kenney, J. D. P., & Lord, S. D. 1991, ApJ, 381, 118
Kenney, J. D. P., Wilson, C. D., Scoville, N. Z., Devereux, N. A. & Young, J. S. 1992, ApJ, 395, L79

Kenney, J. D. P., Carlstrom, J. E., & Young, J. S. 1993 ApJ, 418, 687

Kenney, J. D. P., 1995, in The Interstellar Medium in Galaxies, ed. J. M. van der Hulst (Dordrecht: Kluwer), in press

Kennicutt, R. C., Jr. 1983, ApJ, 272, 54

Kormendy, J. 1993, in Galactic Bulges, ed. H. Dejonge & H. J. Habing, (Dordrecht: Kluwer), 209

Lonsdale, C. J., Helou, G., Good, J. C., & Rice, W. 1985, Cataloged Galaxies and Quasars Observed in the IRAS Survey (Pasadena, Ca: Jet Propulsion Laboratory)

Padin, S. et al. 1991, PASP 103, 461

Pfenniger, D., & Norman, C. 1990, ApJ, 363, 391

Pogge, R. W. 1989, ApJS, 71, 433

Puche, D., Carignan, C., & Wainscoat, R. J. 1991, AJ, 101, 447

Quillen, A. C., Frogel, J. A., & Gonzalez, R. A. 1994, ApJ, 437, 162

Rand, R. J. 1995, AJ, 109, 2444

Regan, M. W., Vogel, S. N., & Teuben, P. J. 1995 ApJ, 449, 576

Roberts, W. W., Huntley, J. M., & van Albada, G. D. 1979, ApJ, 233, 67

Sakamoto, K., Okumura, S., Minezaki, T., Kobayashi, Y., & Wada, K. 1995, AJ, 110, 2075

Sage, L. J. 1993a, A&A, 272, 123

Sage, L. J. 1993b, A&AS, 100, 537

Savage, B. & Mathis, J. 1979 ARA&A, 17, 73

Smith, B. J., Kleinmann, S. G., Huchra, J. P., & Low, F. J. 1987, ApJ, 318, 161
Stauffer, J. R. 1982, ApJS, 50, 517

Tully, R. B. 1989, *Nearby Galaxies Catalog* (Cambridge: Cambridge Univ. Press)

Wakamatsu, K. & Nishida, M. T. 1980, PASJ, 32, 389

Witt A. N., Thronson, H. A., & Capuano, J. M. 1992 ApJ, 393, 611

Wozniak, H., Friedli, D., Martinet, P., & Bratschi, P. 1995, A&AS, 111, 115
Figure Captions

Fig. 1.— An unsharp masked image of NGC 4314 from P1. This high-pass map emphasizes regions within the galaxy where luminosity gradients are changing rapidly. It brings into prominence dust lanes (white) and (for $r \sim 6''$) confirmed regions of recent star formation (black). The sharp gradient of the nucleus also shows up as black. Note the 26'' diameter oval-shaped distribution at p.a. $\sim 58^\circ$, and the dusty region (the “dust bowl”) along the bar, southeast of the nuclear ring at RA = 12$^h$ 22$^m$ 32$^s$.7, Dec = +29$^\circ$ 53$'$ 27$''$. (2000).

Fig. 2.— The uniformly weighted channel maps. The velocity interval is 13 km s$^{-1}$. Channel 9 corresponds to $V = 1075.5$ km s$^{-1}$, while channel 24 is $V = 880.5$ km s$^{-1}$. The contour levels are 3, 4, ... , 10 times our uniform map noise level of 28 mJy beam$^{-1}$. The dynamical center is marked with a cross in each channel.

Fig. 3.— The uniform weight CO contours superposed on the gray scale CO map. The beam size is 2$''$.3 $\times$ 2$''$.2. The contour levels are 0.1, 0.2, ... , 1.0 times the peak intensity of 1.3 Jy beam$^{-1}$ km s$^{-1}$. The 3$\sigma$ level is 0.153 Jy beam$^{-1}$ km s$^{-1}$, slightly higher than the lowest plotted contour.
Fig. 4.— The natural weight CO contours superposed on the gray scale CO map. The beam size is $3''1 \times 2''7$. The contour levels are 0.1, 0.2, ..., 1.0 times the peak intensity of 2.74 Jy beam$^{-1}$ km s$^{-1}$. The 3σ level is 0.165 Jy beam$^{-1}$ km s$^{-1}$, slightly lower than the lowest plotted contour. The extended distribution lies along the primary stellar bar at p.a. = 148°.

Fig. 5.— a) A uniform weight CO intensity contour map superposed on the central region of Fig. 1. The second lowest contour level is 5σ above the noise level. The gray scale is encoded such that local excess (newer stars) is black and local deficit (dust) is white. Note that the elliptical locus of newer stars oriented along p.a. = 58° is devoid of CO. b) A natural weight CO contour map (Fig. 4) superposed on Fig. 1. Note coincidence of CO with the leading edges of the primary stellar bar and with the dust bowl.

Fig. 6.— The uniform weight CO contour map from Fig. 3 superposed on an Hα + [N II] gray scale map (Pogge 1989). The gray scale is encoded to represent the strongest Hα emission as black. Map registration was determined by identifying the Wakamatsu & Nishida (1980) Hα-bright knots A and B.

Fig. 7.— Detailed profiles along p.a. = 148°, the major axis of the primary bar. Surface magnitude and color indices ($\mu_B$, $\mu_B - H$, and $\mu_I - J$) are from P1. The surface density of CO is from the uniform weighted map (Fig. 3). The transformation of CO to molecular gas surface densities is described in the text. We model the gas surface density peak to the SE with a gaussian. The overlay shows the range and quality of the fit. $\mu_{H\alpha}$ is in arbitrary units. In the bottom panel, the ratio $H\alpha/\sigma_{H\alpha}$ provides a qualitative and relative indication of the local SFR. The missing data in $\mu_{I - J}$ and $\mu_{B - H}$ near the nucleus are due to point spread function differences between the visible and short wavelength infrared (SWIR) bandpasses (see P1).

Fig. 8.— Same as Fig. 7, except along p.a. = 58°, the minor axis of the primary bar.

Fig. 9.— Same as Fig. 7, except along p.a. = 0°, through the HII region, knot A.
Fig. 10.— Profiles through the dust bowl perpendicular to the primary bar. The $\mu_B$, $\mu_{B-V}$ and $\mu_{V-I}$ data are from P1. There are no J, H or K data for this region.

Fig. 11.— Visual absorption ($A_V$) and CO surface density ($M_\odot \text{ pc}^{-2}$) are correlated for the gas and dust at the dust bowl.

Fig. 12.— The naturally weighted velocity field superposed on a uniformly weighted gray scale map. The contour interval is $\Delta V = 20 \text{ km s}^{-1}$. We have labeled several contours. The broken circle contour to the NW is $V = 1040 \text{ km s}^{-1}$. The similar contour to the SE is $V = 940 \text{ km s}^{-1}$.

Fig. 13.— a) The rotation curve from OVRO and Combes et al. (1992) data. The OVRO data extend out only to $9''$. The Combes data extend the rotation curve to $r > 120''$. The errors in $V$ are $1 - \sigma$. The error bars in radius represent the beam size. b) The resonance curves. A pattern speed of $3.5 \text{ km s}^{-1} \text{ arcsec}^{-1}$ places the IILR at the end of the nuclear bar (P2) and the OILR coincident with the outer ellipse of newer star formation discussed in P1 and shown in Fig. 14.

Fig. 14.— Velocity residuals produced by subtracting the Fig. 13 rotation curve from the observed natural weight velocity field in Fig. 12. Residuals are superposed upon the Fig. 3 uniform weight CO intensity gray scale map. The velocity interval is $10 \text{ km s}^{-1}$.

Fig. 15.— a) The natural weight CO velocity residual map superposed on the optical unsharp masked data. b) The natural weight CO velocity residual map superposed on H$\alpha$+[N II] from Pogge (1989). The gray scale is encoded to represent the strongest H$\alpha$+[N II] emission as black. Note that the deepest incursions of the decelerating gas terminate in close proximity to large H II regions.
Fig. 16.— Surface I-band intensity (greyscale) from HST (P2) and CO velocity deviations from purely circular motion (contours). $\Delta V = 5 \text{ km s}^{-1}$. The nuclear bar is aligned along p.a.$\approx 148^\circ$.

Fig. 17.— B-I surface color ($\mu_{B-I}$) map of NGC 4314. Encoded such that darker to lighter represents bluer to redder. Note the discrete steps in the color progression along the feature identified with the OILR.
Tables

TABLE 1. Global Properties of NGC 4314

TABLE 2. OVRO Interferometer Results for NGC 4314