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The Origin of the Dust Arch in the Halo of NGC 4631: An Expanding Superbubble?

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ABSTRACT

We study the nature and the origin of the dust arch in the halo of the edge-on galaxy NGC 4631 detected by Neininger & Dumke (1999). We present CO observations made using the new On-The-Fly mapping mode with the FCRAO 14m telescope, and find no evidence for CO emission associated with the dust arch. Our examination of previously published HI data shows that *if* previous assumptions about the dust temperature and gas/dust ratio are correct, then there *must* be molecular gas associated with the arch, below our detection threshold. If this is true, then the molecular mass associated with the dust arch is between 1.5×10^8 $M_\odot$ and 9.7×10^8 $M_\odot$, and likely towards the low end of the range. A consequence of this is that the maximum allowed value for the CO-to-H_2 conversion factor is 6.5 times the Galactic value, but most likely closer to the Galactic value. The kinematics of the HI apparently associated with the dust arch reveal that the gas here is not part of an expanding shell or outflow, but is instead two separate features (a tidal arm and a plume of HI sticking out into the halo) which are seen projected together and appear as a shell. Thus there is no connection between the dust "arch" and the hot X-ray emitting gas that appears to surround the galaxy (Wang et al. 2001).

Subject headings: galaxies: individual(NGC 4631) — galaxies: ISM — galaxies: spiral — radio lines: galaxies

1. Introduction

NGC 4631 is one of the prototypical edge-on spiral galaxies ($i \sim 86\,\mathrm{deg}$). Such edge-on systems allow the study of the interaction between galaxy disks and halos and NGC 4631 displays a number of phenomena associated with disk/halo interaction. It is interacting with two companions, NGC 4627 and NGC 4656, a fact which may be responsible for the high level of star formation in its disk (Rand, Kulkarni & Hester 1992). This star formation activity has lead to an outflow from the disk driven by the input of kinetic energy into the interstellar medium (ISM) by massive stars via stellar winds and supernovae (e.g. Ekers & Sancisi (1977); Wang et al. (1995); Hoopes, Walterbos & Rand (1999)). Close to the disk Rand (2000) has found evidence for an outflow of molecular material in interferometric CO observations of the central part of the galaxy. In the disk beneath this feature are a group of bright HII regions, a peak of radio continuum emission, and a bright X-ray feature, all suggesting a possible starburst driven outflow. Alton, Davies & Bianchi (1999) report a possible dust outflow seen in submm continuum emission at a distance of ~ 1 kpc above the disk.

Recently Neininger & Dumke (1999) have detected 1.2 mm continuum emission from cold dust in the halo out to distances of 10 kpc. The more distant emission appears associated with an HI tidal feature resulting from the interactions with companions, but directly over the central region in NGC 4631, the dust emission forms an arch. The arch encloses an area of enhanced X-ray emission in the halo (Wang et al. 2001), with a morphology very suggestive of a shell of cool gas (associated with the dust), containing a hotter, X-ray emitting gas that may be part of an outflow from the disk.

The nearly edge-on starburst galaxy M82 has been shown to have an outflow of molecular gas from the disk into the halo (Taylor, Walter & Yun (2001); Seaquist & Clark (2001)), so we investigate the possibilities that either an expanding supershell or an outflow including entrained molecular and atomic gas may be responsible for the dust arch in NGC 4631. This galaxy has been much observed in various CO lines recently (Golla & Wielebinski 1994; Young et al. 1995; Rand 2000; Dumke et al. 2001; Paglione et al. 2001) but these have all focused on the star-forming disk. We carried out a mapping program with the FCRAO 14m telescope to search for CO emission from molecular gas in the *halo* of NGC 4631. We also reanalyzed previously published HI data to search for evidence of an outflow near the dust arch. In Section 2 we present our observations, in Section 3 we present our results and discuss their implications, and in Section 4 we summarize the paper.

2. Observations

The observations were obtained with the Five College Radio Astronomy Observatory (FCRAO) 14 m telescope over several runs in January and February, 2002. We observed the ^{12}CO J = 1$\rightarrow$0 line using SEQUOIA, a focal plane array receiver, consisting of 16 pixels.

The On-The-Fly (OTF) observing mode was used, in which the telescope is scanned in rows over the area to be mapped while the receivers are continuously read out. Using OTF mapping with SEQUOIA allowed us to achieve high sensitivity and flat baselines over a large sky area because each position in a map is observed by each of the 16 pixels. Thus we obtain a factor of 4 improvement relative to a single element receiver, plus any pixel-to-pixel irregularities are smoothed away by averaging over all 16 pixels. We used a readout rate of 1 spectrum per second per receiver. An area $10' \times 6'.75$ was mapped in this way. One map took approximately 15 minutes to complete, and the map was repeated 38 times to achieve low rms. The extragalactic filterbanks were used to obtain a bandwidth of 320 MHz with 5 MHz (13 $\mathrm{km\,s^{-1}}$) channels. System temperatures ranged from $\sim$ 450 to 800 K. The pointing was checked every 2 to 4 hours each session using SiO maser sources.

The processing of the OTF scans into a uniformly gridded final map was carried out using an in-house FCRAO reduction package called OTFTOOL (see

http://donald.phast.umass.edu/ ~fcrao/library/manuals/otfmanual.html

for more information regarding the implementation of OTF mapping at FCRAO). OTFTOOL allows the inspection, editing and regridding of the raw OTF data. Once the map of spectra was produced, further reduction and analysis was done with CLASS. A main beam efficiency of $\eta_{MB} = 0.45$ was used used to put the spectra on the T_{MB} scale. We smoothed the data spatially to $60''$ to search for extended, low S/N emission. Unless otherwise stated, all discussion refers to the smoothed data.

3. Results and Discussion

3.1. CO Data: The Molecular Content of the Gas in the Halo of NGC 4631

Figure 1 shows the spectra of our final map displayed at the original velocity resolution of 13 $\mathrm{km\,s^{-1}}$ superposed over the dust emission observed by Neininger & Dumke (1999). CO emission from NGC 4631 itself is clearly present, and corresponds quite closely with the peak of the dust emission at the center of the galaxy. The total integrated intensity from the galaxy is 45.6 ± 4.9 K $\mathrm{km\,s^{-1}}$, compared to 31.4 ± 1.8 K $\mathrm{km\,s^{-1}}$ detected by Golla & Wielebinski (1994) using the IRAM 30-m telescope. These authors note that they did not map the entire galaxy and therefore consider their number a lower limit. Their map has a handful of positions out to about $40''$ above the plane of the disk and didn't cover the dust feature of Neininger & Dumke (1999).

We do not detect CO (1-0) emission coming from the region of the dust arch. The

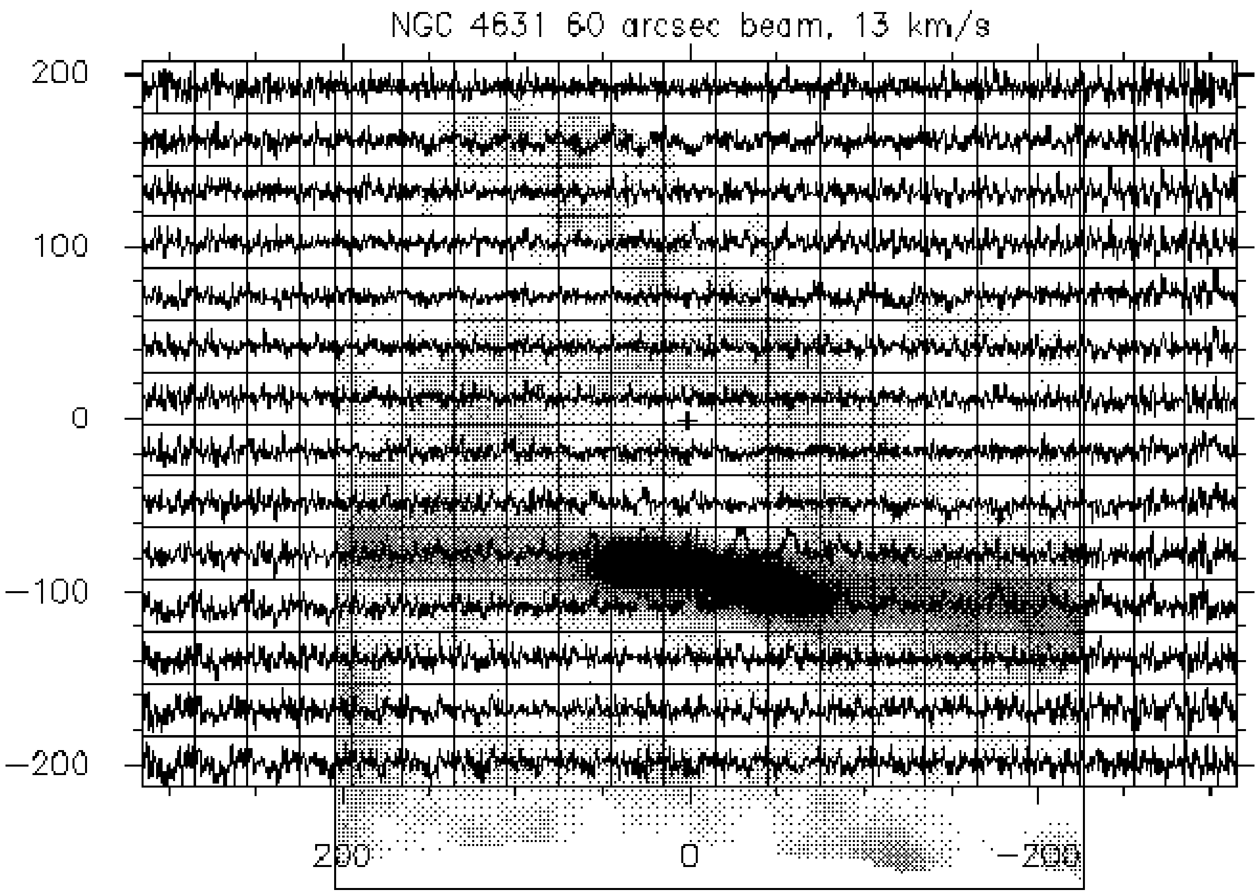

Fig. 1.— Our map of CO (1-0) emission superposed over the central region of the dust emission map of Neininger & Dumke (1999). The CO data cover a 10′× 6′.75 area centered north of NGC 4631. Each plotted spectrum runs from 200 to 1000 $\mathrm{km\,s^{-1}}$ and -0.08 to 0.08 T_{mb}. The spectra shown retain the original velocity resolution of 13 $\mathrm{km\,s^{-1}}$.

rms typical of the spectra in this map is 24 mK. This corresponds to a 3σ upper limit over 3 consecutive velocity channels of 2.9 K km s^{-1}. If we assume a standard Galactic CO-H_2 conversion factor (e.g. 2.3×10^{20} cm^{-2}/ K km s^{-1} from Strong et al. (1988)), this corresponds to an upper limit in column density of 6.6$\times$ 10^{20} cm^{-2} in molecular gas throughout the dust arch. The upper limit for molecular gas mass integrated over the area of the dust arch comes to 3.4$\times$ 10^8 $M_\odot$ for the commonly assumed distance of 7.5 Mpc. We also smoothed the data in velocity to 39 km s^{-1}, achieving an rms of 18 mK, but still found no CO emission. If we average together all the spectra in Figure 1 that overlap the dust emission to search for extended low surface brightness CO emission (Figure 2), we obtain an rms of 11 mK, for a 3σ upper limit of 1.3 K km s^{-1}, or 1.5$\times$ 10^8 $M_\odot$.

For comparison, we note that in our observations of the halo of M82 (Taylor, Walter & Yun 2001) the CO emission had a strength of 36 mK at the same height as the dust arch in NGC 4631. Thus the rms in our map is almost, but not quite, low enough that we could detect similar emission in NGC 4631. However, when we average together all the spectra from the region of the dust arch, the sensitivity improves and we should be able to detect a similar level of emission as is seen in M82. The fact that we don't suggests a genuine distinction between these two edge on systems that both have substantial winds extending into their halos.

At (0,100) in Figure 1 there appears a feature with a S/N ratio of about 3.5σ. Although this location is above the dust arch, it does coincide with dust emission from the tidal feature seen in HI. We received additional observing time to verify this potential CO emission, integrating for eight hours on this location in a "staring" mode – *i.e.* not in a mapping mode. After reaching an rms of 6.7 mK, we find no evidence for this feature in the followup data, suggesting that the peak in Figure 1 comes from random noise.

3.1.1. The Maximum Molecular Mass in the Dust Arch

There are at least three possible explanations for our lack of a detection of CO emission in the region of the dust arch: 1) there is no molecular gas there; 2) there is molecular gas, but the associated CO emission is below our detection threshold; 3) there is CO emission, but it is clumped on scales much smaller than our beam and is undetectable. We discuss each of these possibilities below.

Explanation 1: Neininger & Dumke (1999) estimated the total amount of gas present in the dust arch based upon the dust mass and assuming a gas/dust ratio. We have obtained the HI data of Rand (1994) and estimated the HI associated with the dust arch. The total

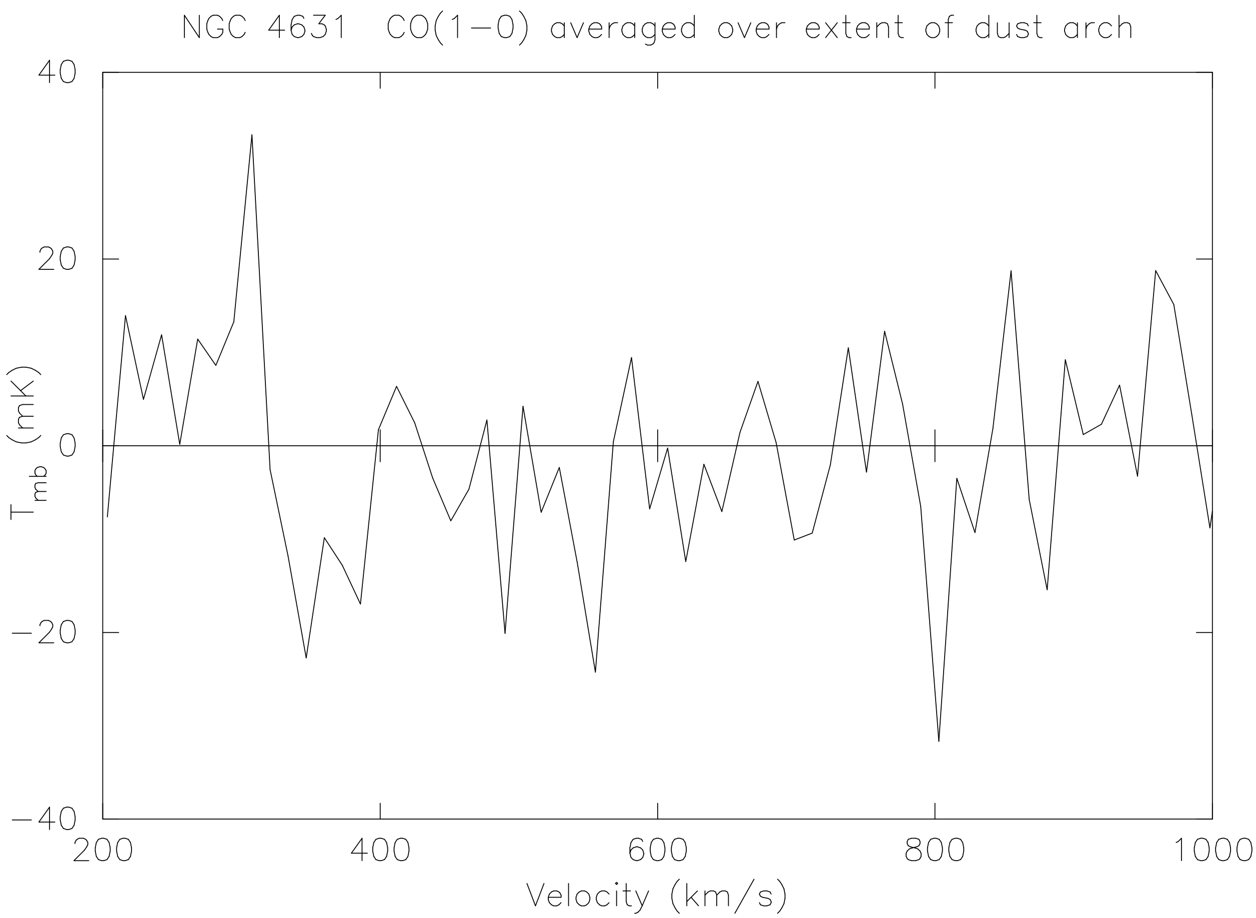

Fig. 2.— The average of all spectra spatially coincident with with the dust arch in the halo of NGC 4631.

gas mass is 1.7×10^9 $M_\odot$, and the HI mass is $7.3 \pm 0.7 \times 10^8$ $M_\odot$, *requiring* $\sim$ *9.7* $\times$ 10^8 $M_\odot$ *of molecular gas to account for all of the observed dust emission.* Thus it seems likely that explanation 1 is not correct – we appear to require at least some molecular gas in the dust arch region. One caveat is that the calculation of total mass by Neininger & Dumke (1999) requires the dust temperature and a gas/dust ratio. Neininger & Dumke (1999) argued that the disks of spiral galaxies with moderate star formation activity have dust temperatures of 15 to 20 K and the dust in the halo is likely cooler, but this is a major source for uncertainty. If the temperature is 5 K cooler, then the inferred gas mass is a factor of 2 greater, but if the temperature is 5 K warmer the mass is 30% less than their estimate. Neininger & Dumke (1999) do not say what gas/dust ratio they used to estimate the gas mass associated with the dust, but likely they used a standard Galactic ratio. It is possible to do away with the need for molecular gas – if the dust temperature is 30 K or hotter, or if the gas/dust ratio is lower than Galactic by at least a factor of 2.5. Existing data cannot speak to either of these possibilities, while the assumptions of Neininger & Dumke (1999) are plausible.

Explanation 2: Our upper limit on molecular gas in the dust arch is 1.5×10^8 $M_\odot$, 6.5 times lower than the molecular gas required to explain the dust emission, 9.7×10^8 $M_\odot$. If the assumptions of Neininger & Dumke (1999) are correct, we should see CO emission. One way to hide CO emission when there is substantial molecular gas present is to increase the CO-to-H_2 conversion factor, such that a large amount of molecular gas has low CO emission. In our calculation of the upper limit, we assumed a typical Galactic value. However, under conditions of low metal abundance or strong UV radiation fields where CO is photodissociated while the H_2 is largely intact, the conversion factor increases. Such conditions can be found in dwarf galaxies (Wilson 1995; Taylor, Kobulnicky & Skillman 1998), or in the outer regions of spiral galaxies (Roberts & Haynes 1994). If the gas in the dust arch originated from the outskirts of NGC 4631 (e.g. by being drawn up out of the plane due to a gravitational interaction with a nearby galaxy) the conversion factor in the gas could be lower than is traditionally assumed. These physical conditions do not necessarily decrease the dust emission – Israel (1997a,b) finds plenty throughout low metallicity galaxies like the Large Magellanic Cloud and NGC 6822.

However, if the CO-to-H_2 conversion factor is too high, then our upper limit on CO emission would correspond to too much H_2 mass. *This allows us to constrain the CO-to-H_2 conversion factor in the region of the dust arch.* The ratio of expected H_2 mass to our upper limit yields the maximum possible conversion factor:

$$\frac{9.7 \times 10^8}{1.5 \times 10^8} = 6.5$$

The molecular mass of the disk of NGC 4631 is $\sim 10^9$ $M_\odot$ (Golla & Wielebinski 1994). It is unlikely that a starburst driven outflow could push half the galaxy's total molecular mass out into the halo but leave the gas still in the disk relatively undisturbed, so most likely 9.7×10^8 $M_\odot$ is an overestimate for the halo molecular gas, and thus the CO-to-H_2 conversion factor is probably close to Galactic.

Explanation 3: A further possibility to explain the large difference between our upper limit and M_{diff} is that the molecular gas is highly clumped, such that the emission is on scales much smaller than the observed distribution of HI or dust. If more that 1.5×10^8 $M_\odot$ of molecular gas were present, and a Galactic CO-to-H_2 conversion factor applied, then we would see CO emission if the molecular gas was smoothly and evenly distributed throughout the dust arch. However, emission could potentially be lost by being averaged together with noise from non-emitting areas if it were highly clumped. This has been shown to happen in the Local Group dwarf irregular galaxy IC 10 by comparing single dish and interferometer CO (1-0) observations (Taylor et al., in preparation, Walter & Taylor, in preparation).

By itself, the lack of CO emission from the dust arch doesn't provide us much with information about the origin of the dust arch *i.e.* is it an expanding supershell that surrounds the hot X-ray gas imaged by Wang et al. (2001)?

3.2. HI Data: The Origin of the Dust Arch

We have also reanalyzed the HI data of Rand (1994) to look for kinematic evidence of a superwind or expanding bubble in the atomic hydrogen spatially overlapping with the dust emission. Figure 3 shows the 1.3 mm continuum dust emission with HI contours superimposed. The HI corresponds well to the dust arch feature. At the top of the dust arch, a tidal arm joins to the galaxy (HI spur 4 from Rand (1994)), complicating the interpretation. There is clearly dust emission associated associated with spur 4 and it joins smoothly onto the western part of the dust arch.

Because of this apparent ambiguity between the dust arch and spur 4 in the maps of 1.3 mm continuum emission and integrated HI intensity, we plot in Figure 4 position-velocity (p-v) diagrams taken parallel to the major axis of NGC 4631, at heights above the disk such that they pass through the region of the dust arch. Several HI features are labeled in the p-v diagrams. At velocities just above 600 $\mathrm{km\,s^{-1}}$ in the p-v cut taken at $83''$ above the disk spur 4 can be seen where it joins the disk on the right side of the galaxy disk. As the cuts move closer to the plane of the galaxy, emission associated with the HI disk becomes more prominent (going from bottom to top in Figure 4). Closer to the disk, at the left side of the

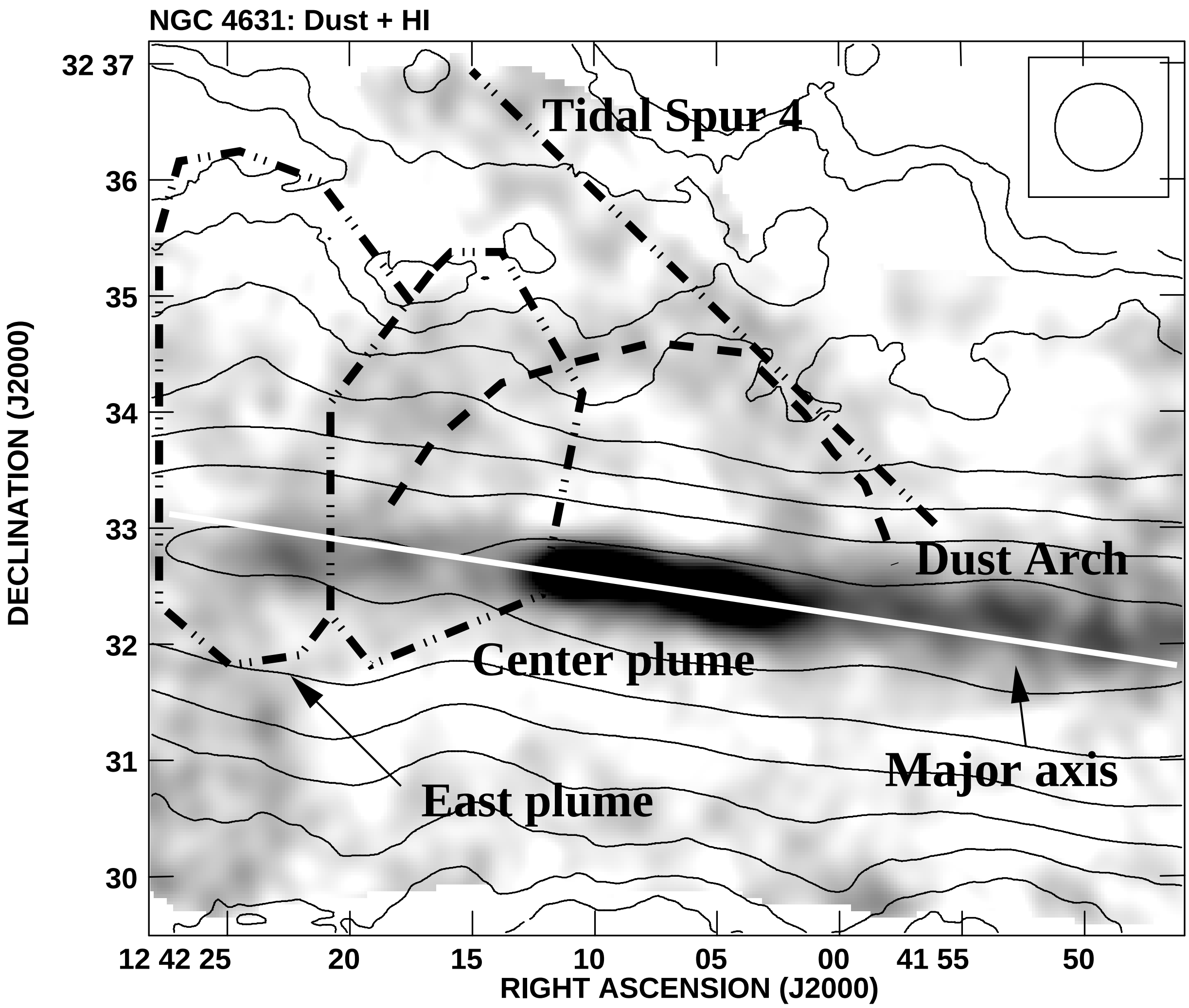

Fig. 3.— Dust emission from the central region of NGC 4631 with HI contours superposed. The HI contours represent 1, 2, 4, 8 16, 32 and 64 $\times 10^{20}$ cm^{-2}. The map of dust emission comes from Neininger & Dumke (1999) and the HI data from Rand (1994). The dust arch is indicated by a dashed line. Kinematic features from Figure 4 are indicated by dot-dash lines and are labeled. The major axis is indicated by the white line.

p-v diagrams at velocities < 700 km s^{-1} is spur 1, visible in the HI maps of Rand (1994). Labeled in the p-v diagram at 80″ above the disk is the "east plume". This feature is visible in Figure 3 projecting up out of the disk at R.A. = 12:42:26. This eastern plume is directly above one of the HI supershells discovered by Rand & van der Hulst (1993) and is visible in their Figure 4a. Another plume, labeled as the "center plume", is most prominent at 74″ above the disk. This feature is seen in Figure 3 where it overlaps spatially with the eastern arm of the dust arch. There is no HI supershell evident below the center plume, and it may tidally formed. We find no kinematic evidence for an expanding shell of HI at the position of the dust arch. In a p-v diagram this would show up as a ring shaped region of enhanced emission.

The HI in the region of the dust arch does not have a single kinematic identity, but instead comes from two distinct features whose proximity gives the appearance of a single feature. The most obvious of these distinct features is the tidal arm extending from southwest to northeast across the halo, known as spur 4. Clearly there is dust associated with spur 4, out to the extent of the region mapped by Neininger & Dumke (1999), and joining smoothly onto the western arm of the arch. The kinematics of the HI in the western arm also show that the gas here is part of spur 4 and not part of an expanding shell or outflow. The HI spatially coincident with the eastern arm of the arch has kinematics distinct from the western side. The spatial distribution of the HI here and its kinematics is similar to that of the east plume, suggesting that the eastern arm of the arch is a weaker HI plume that was not noticed by Rand & van der Hulst (1993). These authors found two other such features (calling them "worms"), so it is not unlikely that there may be more. *Thus the dust arch is formed from dust associated with gas that may only appear to form an arch in projection – tidal spur 4 which forms the west of the arch and the "cap", and an HI plume extending up from the disk of NGC 4631.* It is only coincidence that the apparent arch appears perched suggestively over the X-ray gas in the halo.

3.3. The Dust Arch at Other Wavelengths

NGC 4631 is famous for its large radio continuum halo. It has been observed at a variety of resolutions at several frequencies (e.g. Golla & Hummel (1994), Hummel & Dettmar (1990)) and there are no indications of the arch morphology being traced in the radio continuum. This is not to say that the radio continuum halo is featureless – there are a number of radio spurs that extend up into the halo. Some of these radio spurs are spatially coincident with the HI spurs, including spur 4 that we discussed above. Hummel & Dettmar (1990) argue that the radio spurs are caused by magnetic field lines that have been pulled up out

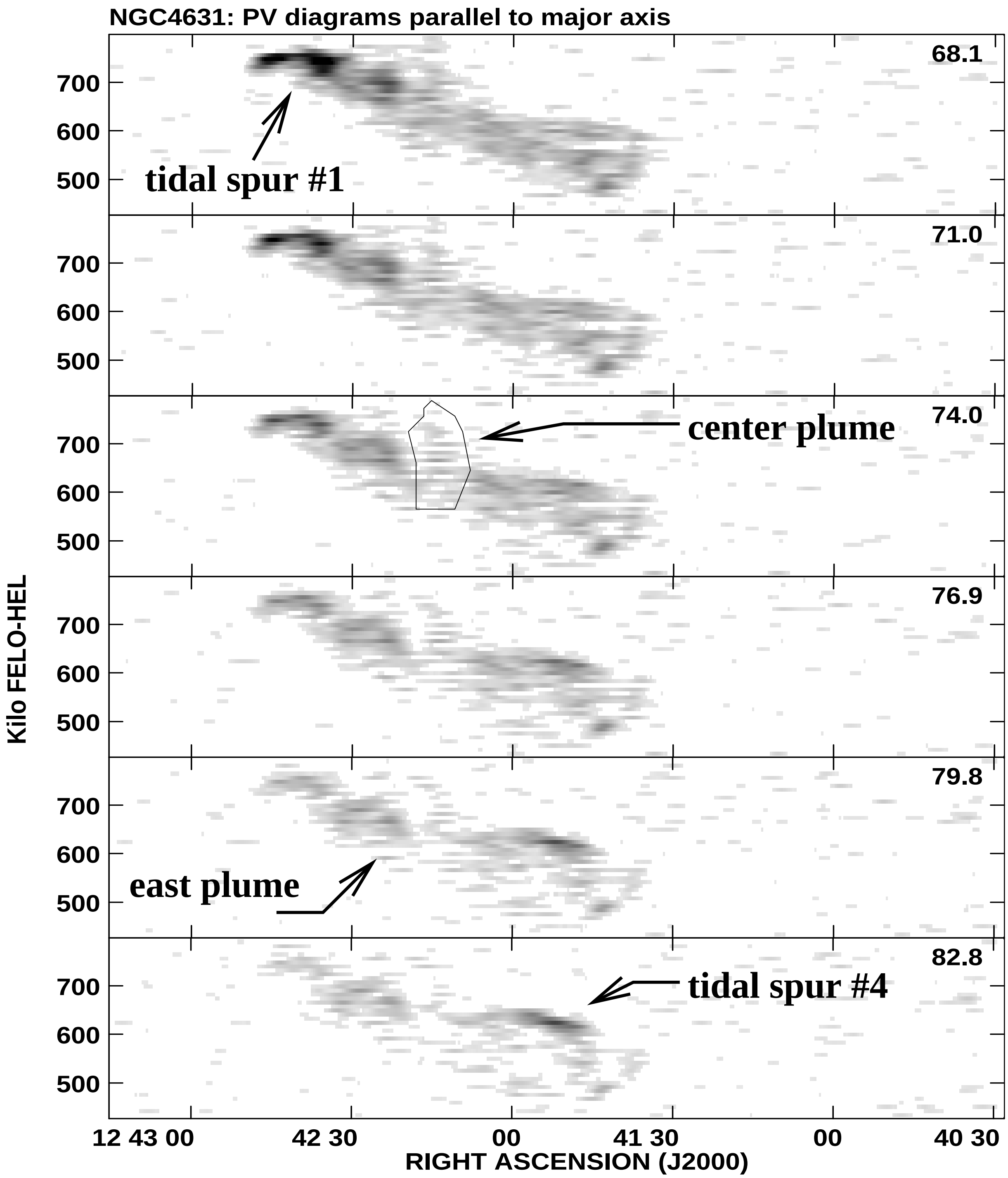

Fig. 4.— Position velocity diagrams from the HI data cube, taken parallel to the major axis of NGC 4631, above the disk. The cuts pass through the position of the dust arch and are labeled with their height above the major axis in arcseconds. Features visible in Figure 3 are also labeled.

of the disk by the gravitational interactions NGC 4631 is experiencing. The fact that the radio continuum emission in the halo does not have an arch shape in the vicinity of the dust arch, but does follow HI spur 4 closely suggests that the dust arch is not a single, coherent physical structure. If the dust arch traced gas that had been blown up out of the disk of NGC 4631 by intense star formation, we would expect the magnetic field lines to have been carried along with it, and that should be reflected in the morphology of the radio continuum emission.

Wang et al. (2001) observed NGC 4631 using ACIS on *Chandra*, finding that the low energy (0.3 – 0.6 keV) diffuse X-ray emission appears to be contained by the dust arch. However, they also point out an absorption feature in this X-ray emission along the minor axis of the galaxy, coinciding with the location of the dust arch. We have identified this part of the dust arch as belonging to HI spur 4, so an equally valid interpretation is that spur 4 is between us and the bulk of the X-ray emission. This is consistent with our interpretation that the arch shape is formed by the chance superposition of spur 4 and a kinematically distinct HI plume.

4. Summary and Conclusions

We used the new OTF mapping capability at the FCRAO 14m telescope to search for CO emission in the halo of the edge-on galaxy NGC 4631, in particular to look for molecular gas associated with the dust arch detected in the halo by Neininger & Dumke (1999). We also examine the HI emission in the region of the dust arch using data from Rand (1994). If previous assumptions by Neininger & Dumke (1999) regarding the dust temperature and gas/dust ratio are correct, we show there must be molecular gas present, because the HI alone wouldn't have enough dust to explain the observed millimeter continuum emission. We set tight upper limits on CO emission and show that for the assumptions made by Neininger & Dumke (1999), the total molecular gas must fall in the range: 1.5×10^8 $M_\odot \leq M_{mol} \leq 9.7 \times 10^8$ $M_\odot$. Since the upper end of that range is almost equal to the total molecular gas in the disk, we favor an amount at the low end of the range. The maximum value of the CO-to-H_2 conversion factor consistent with our range for the molecular mass is 6.5 times the standard Galactic value, but it is probably much closer to Galactic. We also studied the kinematics of the HI that is cospatial with the dust arch. This revealed no evidence for an expanding shell or outflow of HI. Instead, the arch feature is probably formed from two kinematically distinct features, a tidal arm that runs across the halo of NGC 4631, and a plume of HI jutting up out of the disk. The proximity of these two features gives them the appearance of an arch.

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