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# A Molecular Spur in the Edge-on Galaxy NGC 891*

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**Abstract**

The nearest edge-on galaxy, NGC 891, was observed with the Nobeyama Millimeter Array in the CO ($J$=1−0) line. A prominent spur structure of molecular gas emerging vertically from the disk was found at 5.5 kpc from the center of the galaxy. The height of the spur from the galactic disk is 520 pc and its velocity width is narrower than 20 km s$^{-1}$. This is the first detection of vertical features of a molecular line in galaxies other than of those associated with nuclear activity. It provides direct evidence of molecular-gas exchange between the disk and halo. The molecular-gas mass of the spur is $3 \times 10^7 M_\odot$ and its gravitational potential energy is $3 \times 10^{52}$ erg. This spur may be ejected from the galactic disk due to a superbubble or formed by means of the Parker instability, even though some shortage is indicated in each model.

**Key words:** Disk-halo connection — Edge-on galaxies — Galaxies: individual (NGC 891) — Interstellar: clouds — Interstellar: medium — Off-plane structure

## 1. Introduction

Molecular gas is the most massive and dense component of interstellar matter in galaxies and is strongly related to star-formation activity. Due to the lack of spatial resolution of telescopes, most observational research concerning molecular-gas distribution in galaxies has focused on two-dimensional distributions—the so-called "face-on view"—in galactic disks. Galaxies, however, are three-dimensional bodies. The distribution along the third-dimensional axis, perpendicular to the galactic disk, is also important in order to understand the radial flow of matter in galaxies through the galactic halo. Some evidence concerning disk-halo interaction should be found in molecular line observations since one of the most energetic activities in a disk is associated with star-formation activity, including the supernova explosions of young massive stars. The evidence from molecular gas should show that the bulk of interstellar gas is involved in the disk-halo interaction.

Several theoretical models concerned with gas exchange between galactic disks and halos have been proposed; they are called, for example, the "magnetic inflation model" (Sofue 1973), the "rising-and-falling gas model" (Sofue and Tosa 1974), the "galactic fountain" (Shapiro and Field 1976), and the "chimney model" (Norman and Ikeuchi 1989). Observational evidence for these models has been based upon observations of H I and radio continuum in our Galaxy. Regarding galactic data, it is difficult to distinguish between distant galactic-scale structures from nearby local structures. The kinetic distance may provide an estimation of the distance, but is useless for objects which may be beyond the galactic rotation models. In order to avoid this difficulty we require observations of extra edge-on galaxies. Molecular-line observations are more suitable for investigating the detailed structure of interstellar gas in a disk than H I observations. The H I gas is distributed geometrically thicker in the galactic disk than is molecular gas. Moreover, molecular gas is related to star-formation activity, which is a major activity in the galactic disk, except for the nucleus. We therefore conducted CO line observations of the extra edge-on galaxy.

The target galaxy, NGC 891, is the nearest edge-on galaxy. Its distance was estimated to be 8.9 Mpc using the infrared Tully-Fisher relation (Tully and Fisher 1977; Freedman 1990), as well as the H I and H-band photometric data (Aaronson et al. 1982). The inclination of the galactic plane is 89 degrees from the sky plane based upon optical surface photometry (van der Kruit

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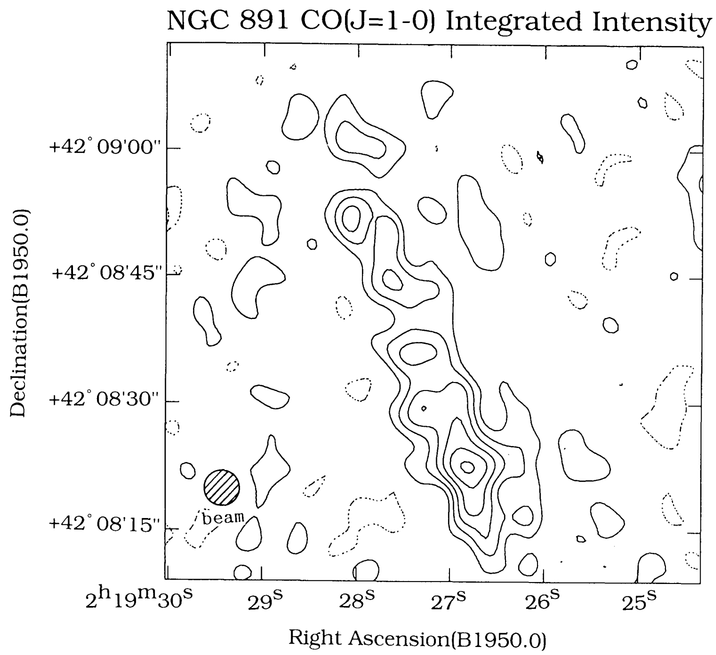


Fig. 1. Map of the $^{12}$CO ($J$=1−0) integrated intensity. The galactic center is located 90″ apart from the center of the map. The primary beam attenuation which is 3 dB at 32.″5 away from the field center was not corrected. The beamsize 4.″5 × 4.″4 is shown in the left-bottom corner. The contour intervals are 0.1 Jy beam$^{-1}$, corresponding about 1.7 rms. The dotted contours show a negative level; the zero level is not plotted.

and Searle 1981; Aoki et al. 1991).

## 2. Observations and Data Reduction

The observations were made in 1989 December and 1990 February in the $^{12}$CO ($J$=1−0) line at 115 GHz using the Nobeyama Millimeter Array (NMA). The synthesized beamsize was 4.″5 × 4.″4 and the field of view due to attenuation of the element antenna was 65″. We chose the field center position at $\alpha$(B1950.0) = 2$^{h}$19$^{m}$27.$^{s}$19, $\delta$(B1950.0) = +42°8′40.″9, 90″ offset from the center of the galaxy along the major axis toward the northern side, where the CO intensity has a local maximum (Sofue et al. 1987). Radio point source 3C 84 was used for phase and flux calibrations and was assumed to be 12.3 Jy at 115 GHz during the observations; this was based upon observations of Uranus and Mars. The backend is a digital spectrometer, called "FX," having 1024 channels and a 320-MHz bandwidth. In order to reduce the noise level we averaged every 24 original channels to one channel in an off-line reduction procedure.

After the standard data procedure in AIPS, including CLEAN, we obtained 10 maps with a 19.5 km s$^{-1}$ velocity width from 289.8 km s$^{-1}$ to 465.2 km s$^{-1}$ with respect to the local standard of rest. The primary beam attenuation which is 3 dB at 32.″5 away from the field center was not corrected.

## 3. Results

The resultant map of the CO (1−0) integrated intensity is shown in figure 1. Most emission is confined to within a thin main ridge which is an edge-on view of the molecular gas disk of the galaxy. This was confirmed by comparing the position angle with that of the galaxy in an optical image, 21 degrees. The confinement of CO emission in the thin disk suggests that most of the molecular gas belongs to population-I objects, which is the same as in our Galaxy. The thickness of the ridge in the integrated intensity map is estimated to be about 7″ with a 4.″5 beam.

In addition to the main ridge, a prominent spur structure can be seen at 406.7 km s$^{-1}$ (figure 2). We believe that this feature is real for the following three reasons: (1) The spur also appears in a dirty map; (2) the corresponding features appear in two maps reproduced from the original dataset with a 9.8-km s$^{-1}$ velocity width, although the signal-to-noise ratio is poorer; (3) and the corresponding features appear in maps reproduced from two visibility datasets divided in the time domain from the original dataset, although the signal-to-noise ratio is poorer.

The velocity width of the spur is less than 20 km s$^{-1}$, since this feature is seen in only one channel map. The height of the spur is about 12″ or 520 pc. Using the

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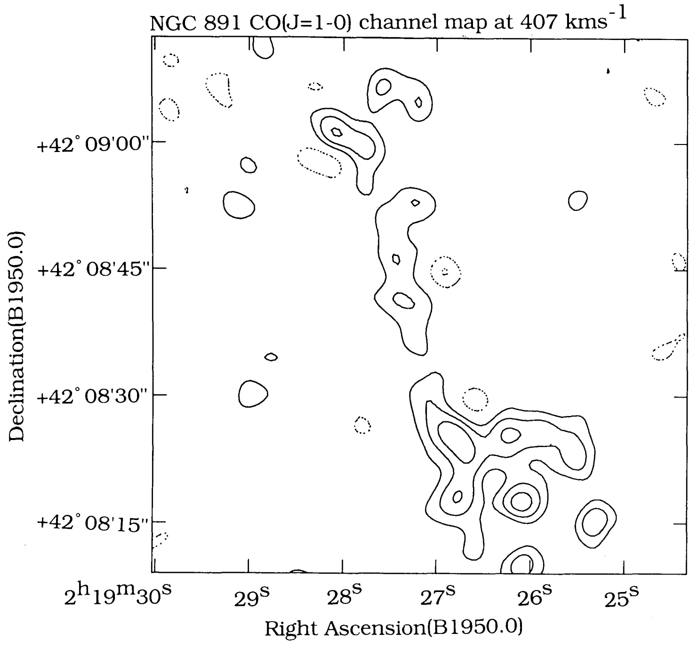


Fig. 2. Channel map at 406.7 km s$^{-1}$ of the same field as in figure 1. The prominent spur structure is perpendicular to the main ridge, which is the disk of the galaxy. The contour intervals are 0.3 Jy beam$^{-1}$, corresponding about 1.4 rms.

standard conversion factor from the $^{12}$CO intensity to the $H_2$ column density for normal galactic disk clouds, $2.3 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ (Solomon and Barrett 1991), the molecular gas mass of the entire spur is $3 \times 10^7 M_{\odot}$, which is about half the mass of the 30 Doradus molecular cloud complex in the Large Magellanic Cloud (Cohen et al. 1988). Using the H I rotation curve (Sancisi and Allen 1979) of the galaxy, the spur was located at 5.5 kpc from the galactic center and 4.6 kpc beyond or before the line of node.

## 4. Discussion

What is the origin of the molecular spur? The displacement of the spur from the population-I disk suggests that the spur is formed either by gas falling onto the disk or by gas ejection from the disk. Falling gas hardly elongates above the disk; above a uniform disk the gravitational potential field is uniform and in the disk the gravitation is the weaker at the closer position to the midplane of the disk. The tidal force therefore cannot cause an elongation for an infalling object. Because of the very elongated morphology, the molecular spur is not the usual type gas cloud falling onto a disk.

The molecular spur cannot be formed by a galaxy-galaxy interaction, since NGC 891 is an isolated, outlying member of the NGC 1023 group of galaxies (G7, de Vaucouleurs 1975). The H I map shows no evidence of warping, even in the outer disk (Sancisi and Allen 1979; Rupen 1991). The molecular spur should therefore be formed by the internal activity of the galaxy.

The gravitational potential energy of the molecular spur with respect to the galactic disk is important in order to check the possibility of spur formation by ejection. The scale height of the stellar disk of NGC 891 has been estimated to be about 0.87 kpc using an isothermal model fit (Kylafis and Bahcall 1987). The mass density of the stellar disk at midplane of NGC 891 is quite difficult to estimate. We assume it to be equal to that near the Sun, $0.1 M_{\odot}$ pc$^{-3}$ (Bahcall 1984). Using the isothermal disk model with a 0.87 kpc scale height, the total gravitational potential energy of the molecular spur is $3 \times 10^{52}$ erg. According to the chimney model (Norman and Ikeuchi 1989) a superbubble ejects interstellar gas from the disk to the halo. The kinetic energy of ejected gas is of the order of $3 \times 10^{51}$ erg, 10-times less than the gravitational potential energy of the spur. It should therefore be difficult to form the spur by only gas ejection from the disk by a superbubble, although the large ambiguity of the mass density of the stellar disk causes the large ambiguity concerning the gravitational potential energy.

Shibata and Matsumoto (1991) presented a model concerning the formation of a spur-like structure perpendicular to the galactic disk due to the Parker instability. In this model most of the gas in the spur moves hori-

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zontally from inter-spur regions, not vertically from the disk. Confinement of gas in the elongated spur is supported by a standing shock wave. The horizontal velocity of the gas is on the order of the sound velocity. The observed velocity width of the molecular spur, which is less than 20 km $s^{-1}$, is consistent with the model. However, this model requires a quick conversion from atomic gas to molecular gas since the gas above the disk is atomic. Radio continuum observations with VLA shows a complicated distribution of the polarization angles near to this spur (Sukumar and Allen 1991). It is difficult, however, to actually know the structure of the magnetic field from this image, due to strong depolarization and the Faraday effect.

How common is a spur structure like this in spiral galaxies? In order to answer this question we require greater coverage of more galaxies. In our Galaxy, molecular clouds of $10^5 M_{\odot}$ are found 100–200 pc above the galactic disk (Grenier et al. 1989). The molecular spur of NGC 891 may be a huge version of such clouds. In the halo of our Galaxy several young stars which should be formed in the halo were found (e.g., Keenan and Lennon 1984; Brown et al. 1989). If the molecular spur structure is very common in galaxies, then molecular gas for star formation in the halo would be supplied by the molecular spur.

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