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CO Observations of the Edge-on Galaxy NGC 891

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Abstract

High-resolution (HPBW=16″) ^{12}CO (J=1–0) line observations have been made of the NE quadrant of the edge-on galaxy NGC 891. The line intensity distribution along the major axis shows that the molecular gas disk is composed of two components: a main disk having a deep depression toward the center and a nuclear disk with a sharp peak at the center. The main disk has a broad ring structure of radius 5–10 kpc with the total H_2 mass of $6\times10^9\,M_\odot$ and extends at least up to 15 kpc from the galaxy center. Several arms and large-scale clumps are found on the position velocity diagram along the major axis. The CO rotation curve agrees with that of H I, but the CO disk is located in an inner region than H I and coincides with the radio continuum disk. The nuclear disk is tightly concentrated within about 500 pc of the galactic center, and its total H_2 mass is estimated to be about $3\times10^8\,M_\odot$ with the mean H_2 density as large as $\sim10^3\,H_2\,cm^{-3}$ for an assumed thickness of 100 pc and a diameter of 1 kpc. The nuclear disk has a large velocity dispersion and is suggested to have a relation to the central activity associated with a strong radio continuum core. The present CO results support the view that the large-scale characteristics and morphology of NGC 891 and our Galaxy are very similar.

Key words: CO line emission; Molecular hydrogen; Nuclear disks; Rotation curves; Spiral galaxies.

1. Introduction

The large-scale distribution of CO line emission in disk galaxies has an important implication for understanding the structure and dynamics of the gaseous content and the evolution of the star-forming activity on a galactic scale. In the case of edge-on galaxies a one-dimensional scan map can give fairly complete information about the large-scale CO distribution in an appropriate observing time. This paper is the first of

* Nobeyama Radio Observatory, a branch of the Tokyo Astronomical Observatory, University of Tokyo, is a facility open for general use by researchers in the field of astronomy, astrophysics, and astrochemistry.

a series to report high-resolution CO observations of edge-on galaxies using the NRO 45-m telescope. We present results on a typical edge-on galaxy of Sb type, NGC 891.

NGC 891 has been observed in ^{12}CO (J=1–0) using the FCRAO 14-m telescope with a resolution of 45″ (Solomon 1982, 1983). The CO intensity distribution along the galaxy plane has a dip at the center and maxima at distance of 1′ from the center. [Angular distance of 1′ corresponds to 4 kpc for a distance to the galaxy of 14 Mpc (Sancisi and Allen 1979).] This suggests a ringlike distribution of molecular hydrogen gas of radius 5 kpc and a central hole. A similar ring plus central hole structure has been found in some other Sb galaxies (Young 1983). However, it is well known that the Milky Way Galaxy, a typical Sb galaxy, has a strong concentration of molecular gas toward the galactic center forming a dense molecular disk (Sanders et al. 1984). It is therefore interesting to clarify by high-resolution observations whether Sb galaxies have a nuclear molecular disk in general or the nuclear disk in our Galaxy is an exceptional phenomenon. This may also give an important key to understand the origin of the central activity which may be related to an accretion of gas toward the center.

Another important purpose of the high-resolution CO observations of edge-on galaxies is to derive a rotation curve in CO without the ambiguity of the inclination angle. A CO rotation curve should provide a substantial clue to the dynamics of the galaxy, especially for the central region where the H I line emission has a depression, giving poor information about the nuclear disk (Sancisi and Allen 1979). We may also be able to resolve spiral arms in the molecular content through the analysis of the position-velocity structure along the galactic plane.

2. Observations

The observations were made on February 25, 1986 using the 45-m telescope. The antenna had a HPBW of 16″, and the pointing accuracy was better than 5″ through the observations. The main-beam efficiency was 36%. We used a cooled Schottky-barrier diode mixer receiver combined with an acousto-optical spectrometer of 250-MHz bandwidth, or 650-km s^{-1} velocity coverage at the CO (J=1–0) frequency. The spectrometer had 2048 channels which gave a velocity resolution of 0.6 km s^{-1}. We, however, averaged the data over every 32 channel interval to increase the signal-to-noise ratio, and the final velocity resolution was 10 km s^{-1}. The system temperature was about 700 K. We used a position switching mode with a multiple on-positions and two off-positions at offsets in right ascension of $\pm 10'$ from the galaxy center. The total integration time per one data point was about 20 min. The rms noise of the resultant profiles was about 20–40 mK.

The reference center position was taken at R.A. (1950)=$2^{h}19^{m}24\overset{s}{.}3$, Decl. (1950) =42°07′17″. The position angle of the major axis (X-axis) of NGC 891 was taken as 21°. We observed several points at a $7\overset{''}{.}5$ separation along the minor axis (Z-axis) and along a line crossing the plane at X=60″ to find the maximum position of the CO intensity across the galactic plane. Here X is the distance from the center toward NE along the major axis. After finding the maximum position we drew a line by which we define the major axis of the CO disk. Then we took spectra along this major axis with spacings of $7\overset{''}{.}5$ for $-30'' \le X \le 30''$ and with spacings of 15″ for $30'' \le X \le$

225″. The systemic velocity of the galaxy center was taken as 524 km s^{-1} (Sancisi and Allen 1979).

3. Results

(i) Spectra

Figure 1 shows examples of the obtained CO line spectra along the major axis for $X=0''$ through 225″ with spacings of 15″. We detected the CO emission on every point up to $X=225''$ at 0.1–0.2 K $T_A{}^*$ level. The intensities are corrected antenna temperature $T_A{}^*$ calibrated with respect to the standard source Ori A with $T_A{}^*=$

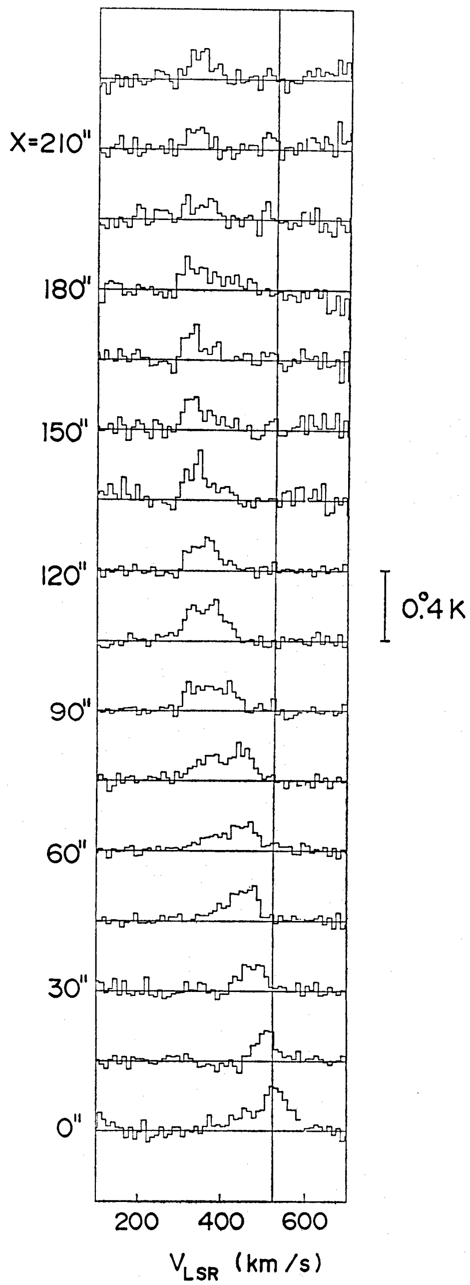

Fig. 1. Examples of the obtained spectra of the ^{12}CO line for the edge-on galaxy NGC 891 along its major axis at 15″ intervals.

35 K. The highest temperature was recorded toward the galactic center with $T_A^*=0.25$ K. The antenna temperature along the major axis varies between 0.1 and 0.2 K with the maximum at $X=105''$ where $T_A^*=0.22$ K. It is remarkable that T_A^* is as high as 0.15 K even at $X=225''$ or 15 kpc from the center. The velocity at the peak antenna temperature varies from $V_{LSR}=524$ km s^{-1} at $X=0''$ to 300–350 km s^{-1} beyond $X=90''$, showing clearly the rotation of the galaxy. We also note that the line profiles bifurcate into double peaks at $X=75$–$120''$, which suggest that spiral arms have been resolved. Velocity profiles along the minor axis show a strong concentration of the CO disk toward the galactic plane. We find no significant velocity variation along the minor axis.

(ii) Distribution of Intensity: Main Disk+Nuclear Disk

Integrated intensities $I_{CO}=\int T_A^* dV$ are plotted against X and Z in figure 2, where the data at $-30''\leq X\leq 30''$ are the sum of several independent observations at grid intervals of 7.″5 and 15″. The error in I_{CO} is estimated from $\Delta I_{CO}=\Delta T_A^*(W\Delta V)^{1/2}$, where ΔT_A^* (0.03 K) is the rms noise in the spectrum, W (300 km s^{-1}) is the range of integration and ΔV (10 km s^{-1}) is the velocity resolution. In the present case we have typically $\Delta I_{CO}=1.6$ K km s^{-1}. The figure shows that the radial distribution of I_{CO} is composed of two components; one is the broadly distributed main-disk component with the maximum at $X=60''$, tailing as far as 225″ and more from the galaxy center. The other is a strong concentration at $X=0''$ which we call the nuclear-disk component.

The main disk has a peak intensity of about $I_{CO}=24$ K km s^{-1} at $X=60''$ or 5 kpc, suggesting that the molecular gas is distributed on a broad ring of radius $R=$ 5–10 kpc. This distribution well resembles that of our Galaxy which has also a 5-kpc molecular ring (Scoville and Solomon 1975). The main-disk component has a

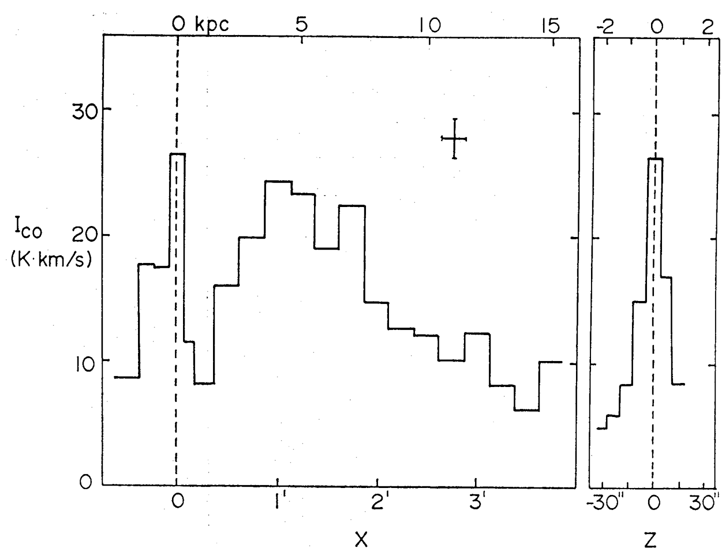

Fig. 2. Distributions of the integrated CO intensity I_{CO} (K km s^{-1}) along the major axis (X) and along the minor axis (Z). Note that the nuclear disk tightly concentrated to the galaxy center has been clearly detected. The HPBW of the telescope and the error in I_{CO} are indicated with the cross.

deep dip toward the galactic center. If we subtract the nuclear disk component, the main disk intensity at $X=0''$ is as low as $I_{CO}=5$ K km s^{-1}. The main disk is well visible at least up to $X=225$ km s^{-1} or 15 kpc, and appears to extend further away beyond this radius. In addition to the broad ringlike distribution, the main disk component is superposed with several peaks possibly caused by tangential cross sections of spiral arms, which are seen at $X=60''$ (5 kpc), 105″ (7.5 kpc), 180″ (12 kpc), and 225″ (15 kpc).

The nuclear disk component is as narrow as about 20″ at half maxima in the X-direction, and is seen from $X=-15''$ through 7″.5. If we take into account the beam width of 16″, the X extent (diameter) is about 12″ or 0.8 kpc. This is comparable to that of the nuclear molecular disk of our Galaxy (Liszt and Burton 1978). The peak intensity at the center is as high as 26 K km s^{-1}, and if we subtract the main disk component, the net contribution from the nuclear disk is approximately 20 K km s^{-1}. The intensity distribution along the minor axis (Z) shows a high concentration toward the galactic plane. However, the Z distribution seems to have a broad tail extending to a height of $Z=\pm 20''$, which may be either due to a tilt of the disk or to the main disk component having a larger thickness. If we subtract this broadly extended component, the remaining nuclear disk has an apparent Z width of about 16″. This indicates that the disk thickness is less than a few hundred parsecs.

(iii) The Masses

For the FCRAO 14-m telescope, which had a main-beam efficiency of 0.6, the surface density of molecular hydrogen has been determined from the CO intensity using the expression,

$$N_{H_2}=3.6\times 10^{20}\int T_A^* \, dV \, (\mathrm{cm}^{-2}) \,, \qquad (1)$$

where T_A^* is the antenna temperature calibrated with respect to Ori A with $T_A^*=60$ K [Solomon (1983); see also Young and Scoville (1982)]. For the 45-m telescope, which had a main-beam efficiency of 0.36, we have

$$N_{H_2}=6.2\times 10^{20}\int T_A^* \, dV \, (\mathrm{cm}^{-2}) \,. \qquad (2)$$

By extrapolating the X distribution of I_{CO} in figure 2, we obtain the radius of the outer edge of the CO main disk as about 5′ or 20 kpc. By integrating the obtained intensities along the major axis we find the total H_2 mass of the observed part in the NE half is $M_{H_2}=3\times 10^9\ M_\odot$. As the Z-distribution at $X=60''$ shows a wider extent than our beam width, we must take the mass as a lower limit. We may therefore conclude that the total H_2 mass in the whole main disk is greater than $6\times 10^9\ M_\odot$.

The nuclear disk, which has an apparent extent of about $20''\times 16''$, has a total H_2 mass of $M_{H_2}=3\times 10^8\ M_\odot$ for the intensity at the center of 20 K km s^{-1}. If the disk has a thickness of about 100 pc, similarly to our Galaxy, and a radius of about 0.5 kpc, the gas density in the disk is estimated as large as 10^3 H_2 cm^{-3}.

(iv) Kinematics and Rotation Curve

Figure 3 shows a position-velocity (X-V) diagram along the major axis. The rotation curve as derived from the terminal velocities as drawn by the dashed line

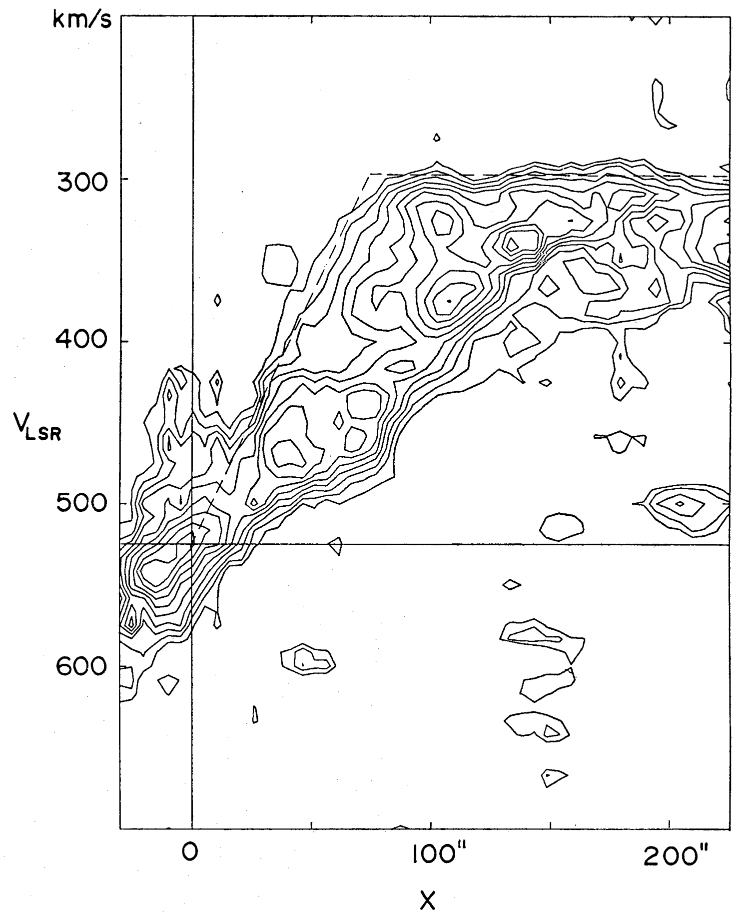

Fig. 3. The velocity structure of the CO line emission along the major axis. The outer envelope (terminal velocities) defines the rotation curve (dashed line), which agrees with the H I rotation curve of Sancisi and Allen (1979). The contours are in steps of 20 mK T_A* and the lowest contour is at 40 mK.

coincides with the H I rotation curve of Sancisi and Allen (1979). The rotation velocity increases linearly until $X=60''$, where the velocity can be expressed by a rigid rotation as $V=(225\ \mathrm{km\ s^{-1}}/75'')X$. Here we define V as $V=V_{\mathrm{LSR}}-524\ \mathrm{km\ s^{-1}}$. The rotation velocity attains a maximum at $X=100''$ and then remains almost constant at $V=225\ \mathrm{km\ s^{-1}}$ at least up to $X=225''$ (15 kpc). From the rotation curve the dynamical mass contained within 15 kpc is estimated as $M_{\mathrm{d}}=2\times10^{11}\ M_{\odot}$.

The main disk component in the X-V diagram has several peaks. A large complex is seen at $X=50''$–$75''$ and is composed of two components at $V=50$ and $90\ \mathrm{km\ s^{-1}}$. A condensation is found at $X=110''$ and also bifurcates into two components at $V=150$ and $200\ \mathrm{km\ s^{-1}}$. There are two more complexes at $X=140''$ ($V=190\ \mathrm{km\ s^{-1}}$) and at $X=225''$ ($V=190\ \mathrm{km\ s^{-1}}$). These complexes might be due to tangential cross sections of the spiral arms. However, the ridge of the peak intensities connecting the major condensations at $X<150''$ runs on a straight line expressed by $V=(200\ \mathrm{km\ s^{-1}}/150'')X$. The line does not coincide with the rotation curve but coincides with rotation of a circle of radius $\sim150''$ (~10 kpc). Therefore, the condensations might alternatively be large cloud complexes distributed along such a circle. If this is the case, the galaxy has a 10-kpc ring of molecular hydrogen, and the apparent peak at $X=60''$ (5 kpc) in the intensity distribution (figure 2) is due to local complexes on the ring at nearer or farther side of the galactic center. Sancisi and Allen (1979) have also pointed out that the H I ridge on the X-V diagram may be expressed by a model that the H I gas is located on a ring of radius 16 kpc.

The nuclear disk is clearly seen as the strong CO condensation at $X=0''$. The disk is elongated on the X-V plane in the same sense as the galactic rotation. The main ridge of the nuclear disk is fitted with a straight line of $V=(30 \text{ km s}^{-1} \text{ kpc}^{-1})X$, and a dynamical mass within 1 kpc of the center is estimated to be $\sim 10^8 M_\odot$. This value is smaller than the H_2 mass derived directly from the CO intensity, $M_{H_2}=3\times10^8 M_\odot$. This fact may indicate either that the disk is not in a dynamical balance with the rotation but supported by other forces like the random motion as discussed below, or that the conversion factor from I_{CO} to H_2 mass in equation (2) is not valid any more for the nuclear region.

The velocity dispersion near the center is as large as 100 km s^{-1} between 20% levels of the peak temperature. The high dispersion may partly be due to internal motion of the gas and partly due to the steep gradient of the rotation curve. If the velocity dispersion is due to the random motion of the gas in a dynamical balance with gravitation and confined within the radius of several hundred parsecs, the central mass is about $10^9 M_\odot$, not inconsistent with the H_2 mass. We also cannot exclude the possibility that the gas motion comes from some violent phenomenon which causes a high expansion motion. Alternatively, it is possible that the gas is falling in toward the center at a velocity of 50 km s^{-1}. We may here recall that a high dispersion has also been known for the molecular gas in the central region of our Galaxy (Sanders et al. 1984), where no simple rotation can account for the velocity structure.

(v) Comparison with H I and Continuum Observations

Figure 4 shows a comparison of the CO intensity distribution along the major axis with those of the H I line emission and of the radio continuum emission at 1.4 GHz obtained with WSRT (Sancisi and Allen 1979; Allen et al. 1978). The H I and

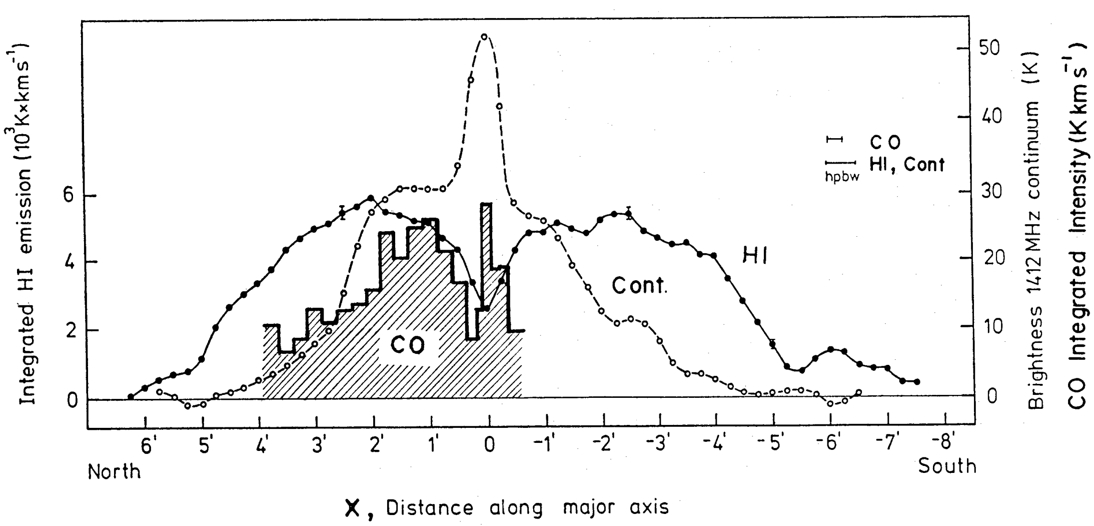

Fig. 4. Comparison of the CO intensity distribution along the major axis with the H I and the radio continuum emissions at 1.4 GHz (Sancisi and Allen 1979; Allen et al. 1978).

continuum observations had a spatial resolution of $25'' \times 27''$.

The CO main disk component has a similar distribution to that of the broad disk of the continuum emission. The H I gas is more widely distributed with a peak at around X=2–3′. The H I gas has a deep dip near the center which Sancisi and Allen (1979) attributed to self absorption and/or absorption against the central continuum emission. The CO nuclear disk component well coincides with the continuum peak at the center. This fact shows a significant correlation between the nuclear activity observed as the strong continuum core and the existence of the dense CO disk.

(vi) Comparison with Our Galaxy

It has been pointed out that NGC 891 and our Galaxy are similar in their optical, H I and radio continuum appearances (Sancisi and Allen 1979). However, it has not been made clear whether NGC 891 possesses a nuclear disk of molecular gas from the previous CO observations with the FCRAO 14-m telescope (Solomon 1983), whereas the Milky Way has a clear nuclear CO concentration. The existence of the nuclear CO disk in NGC 891 is now proved by the present high-resolution observations, and the separation of the CO disk into the main and the nuclear disksc onfirms the similarity between NGC 891 and the Milky Way Galaxy.

4. Summary

High-resolution CO observations of the edge-on galaxy NGC 891 were carried out to obtain the distributions of molecular hydrogen along the major and minor axes. The conclusions may be summarized as follows:

(1) The CO disk is separated into the main and nuclear disks. The main CO disk suggests a ringlike structure of radius 5–10 kpc and is shown to extend at least up to X=15 kpc. The total H_2 mass is more than $6 \times 10^9\ M_\odot$.

(2) Several arms or large clumps of H_2 gas are recognized on the position-velocity diagram.

(3) The CO rotation curve agrees with the H I rotation curve, showing a constant rotation at 225 km s^{-1} beyond R=5 kpc.

(4) The main CO disk is located in an inner region than the H I disk, whereas it coincides with the radio continuum disk.

(5) A nuclear disk has been detected for the first time for an external Sb galaxy. The disk is as tight as several hundred parsecs in radius and very thin. The total H_2 mass is about $3 \times 10^8\ M_\odot$. The central region has a high velocity dispersion.

(6) The high concentration of the molecular gas toward the center may be related to the central activity as indicated by the strong core source in the continuum radio emission.

(7) The present CO results support the view that the characteristics of NGC 891 and of our Galaxy are very similar.

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