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External Fueling and Stochastic Ignition of Starburst in Isolated Galaxies

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Abstract

Intergalactic gas clouds are captured by spiral galaxies due to the ram-pressure friction existing in gaseous halos and disks. The captured clouds are rapidly accreted toward the central region, fueling the nucleus, which may trigger starburst. This could be a triggering mechanism for starburst in isolated galaxies.

Key words: Accretion; Galaxies; Gas halo; Intergalactic gas; Ram pressure; Starburst.

1. Introduction

A typical starburst galaxy, such as NGC 253, is an isolated galaxy (Rieke et al. 1980). Starburst is therefore not a particular phenomenon to interacting galaxies. Starburst in an isolated galaxy must be triggered by some mechanism other than gravitationl interaction, although the interaction hypothesis (e.g., Noguchi 1988) has been successfuly applied to both paired and merging galaxies.

We have proposed a ram-pressure accretion model of intergalactic gas clouds (Wakamatsu 1990). We discussed the possibility of the accretion of clouds and fueling the nuclei of elliptical galaxies embedded in extended hot gaseous halos. In the present paper we apply this model to spiral galaxies. We show that intergalactic H I clouds are easily captured and accreted toward the central region, which may stochastically fuel and trigger starburst in isolated galaxies. A detailed description of this model, including a discussion of confinement and cascade processes of intergalactic H I clouds, will be given in a forthcoming paper (Sofue and Wakamatsu 1991a, b).

2. Ram-Pressure Accretion by Spiral Galaxies

The ram pressure caused by intergalactic gas has been investigated from the standpoint of gas stripping from spiral galaxies (Gunn and Gott 1972; Gisler 1979; Farouki and Shapiro 1980). We consider here just the opposite case: accretion of intergalactic gas clouds, which are often observed in the H I line emission (Gottesman and Weliachew 1977; Weliachew et al. 1978; Haynes et al. 1979; Mathewson et al. 1979; van Woerden 1985; Sancisi et al. 1987), by ram-pressure friction existing in the halo and disk gases of spiral galaxies.

Evidence for the existence of a halo component around spiral galaxies has been obtained for several edge-on galaxies. Our Galaxy has an ionized gaseous halo extending for 3–5 kpc from the galactic plane with a gas density of $\sim 10^{-3} m_{\rm H}\ {\rm cm}^{-3}$(de Boer and Savage 1983). NGC 4631 is embedded in an extended H I envelope (Weliachew et al. 1978). This galaxy also has an extended magnetic corona of several kiloparsec extent, which would be associated with a significant amount of ionized gas (Hummel et al. 1988). M82 is also surrounded by an extended envelope comprising of H I gas, molecular gas, and hot (X-ray) corona (Gottesman and Weliachew 1977; Sofue et al. 1991; Tsuru et al. 1990). Hence, we may suppose that some spiral galaxies, though it might not be true for all, possess an extended gaseous corona in addition to the disk.

The ram-pressure (dynamical pressure) force is given by $-\pi R^2 \rho(r) \mathit{\Delta} V^2$, where R is the cloud radius, $\rho(r)$ the gas density through which the cloud is moving, and $\boldsymbol{\Delta V} = \boldsymbol{v} - \boldsymbol{V}$ the relative velocity of a cloud with respect to the halo gas which is moving (rotating) at a velocity $\boldsymbol{V}$. The equation of motion can be written as

$$m \frac{d^2 \boldsymbol{r}}{dt^2} = m \frac{\partial \mathit{\Phi}}{\partial \boldsymbol{r}} - \pi R^2 \rho(r) \mathit{\Delta} V \boldsymbol{\Delta V}, \tag{1}$$

where $\boldsymbol{v} = d\boldsymbol{r}/dt$ and $\boldsymbol{r} = (x, y, z)$ is the cloud position with respect to the galaxy center. The cloud mass is given by $m = (4\pi/3) R^3 \rho_{\rm HI}$, with $\rho_{\rm HI}$ being the H I gas density of the cloud. We assume here that $R \sim 0.5$ kpc and $\rho_{\rm HI} \sim 0.5\ m_{\rm H}\ {\rm cm}^{-3}$, so that $m \sim 6.4 \times 10^6 M_{\odot}$. The gravitational potential of the galaxy is approximated by a modified Miyamoto and Nagai potential (Nagai and Miyamoto 1976),

$$\mathit{\Phi} = \sum_{i=1}^{3} \frac{G M_i}{\sqrt{\varpi^2 + \left(a_i + \sqrt{z^2 + b_i^2}\right)^2}}, \tag{2}$$

where $\varpi = (x^2 + y^2)^{1/2}$; M_i, a_i and b_i are the masses and scale radii for the i-th mass component of the galaxy. We assume three mass components: a central bulge ($i = 1$), a disk ($i = 2$), and a massive halo ($i = 3$). The adopted values for the parameters are given in table 1.

The density distribution of gas around a spiral galaxy is approximated by

$$\rho(\varpi, z) = \rho_{00} + \frac{\rho_0}{(\varpi/\varpi_0)^2 + (z/z_0)^2 + 1} + \frac{\rho_1}{(\varpi/\varpi_1)^2 + (z/z_1)^2 + 1}, \tag{3}$$

where ρ_0, ϖ_0 and z_0 are parameters representing the distribution of halo gas density; ρ_1, ϖ_1 and z_1 are those for the disk component; and ρ_{00} is the intergalactic (intracluster) gas density. The values of the parameters are given in table 2. The rotation

Table 1. Parameters for the gravitational potential.

i	Mass component	$M_i(M_\odot)$	a_i (kpc)	b_i (kpc)
1	Central bulge	2.05×10^{10}	0	0.495
2	Disk	2.547×10^{11}	7.258	0.520
3	Massive halo	3×10^{11}	20	20

Table 2. Parameters for the disk, halo and interglactic gas components.

Galactic and intergalactic gases	
ρ_{00}	$2.5 \times 10^{-6}\ m_{\rm H}\ {\rm cm}^{-3}$
ρ_0	$2.5 \times 10^{-3}\ m_{\rm H}\ {\rm cm}^{-3}$
ϖ_0	15 kpc
z_0	10 kpc
ρ_1	$0.25\ m_{\rm H}\ {\rm cm}^{-3}$
ϖ_1	10 kpc
z_1	0.2 kpc
H I cloud	
$\rho_{\rm HI}$	$0.5\ m_{\rm H}\ {\rm cm}^{-3}$
R	0.5 kpc
$m = (4\pi/3)R^3\rho_{\rm HI}$	$\sim 6.4 \times 10^6 M_\odot$

velocity in the galactic plane is about 200–230 km s^{-1} . The halo gas is assumed to be rotating around the z-axis at a velocity such that its centrifugal force balances the gravity toward the z-axis, while it is at rest in the z-direction in hydrostatic equilibrium. Hence, the rotation in the halo is much slower than in the galactic plane.

3. Orbits and N-Clouds Simulation

Figure 1 shows the calculated orbits for clouds injected along hyperbolic orbits within the galactic plane. A cloud injected on a "retrograde" orbit moves against the halo and disk rotation, so that it suffers from a strong drag, and is decelerated and easily captured by the galaxy. Once it is captured, its orbiting velocity is forced to reach that of disk rotation by ram friction until it attains corotation with the disk gas. The accretion then stops, and the cloud orbits around the galaxy on a ring. On the other hand, if a cloud approaches the galaxy on a "direct encounter" orbit, its speed relative to the halo and disk gas is smaller, so that the ram friction is small and the accretion is less effective. The capture of retrograde clouds is thus much easier than that of direct ones, and the accretion rate of intergalactic clouds is significantly asymmetric about the x-axis.

Figure 2a shows the orbits for direct encounters when the initial orbital plane is inclined to the galactic plane by 45°; Figure 2b shows the retrograde cases. Capture

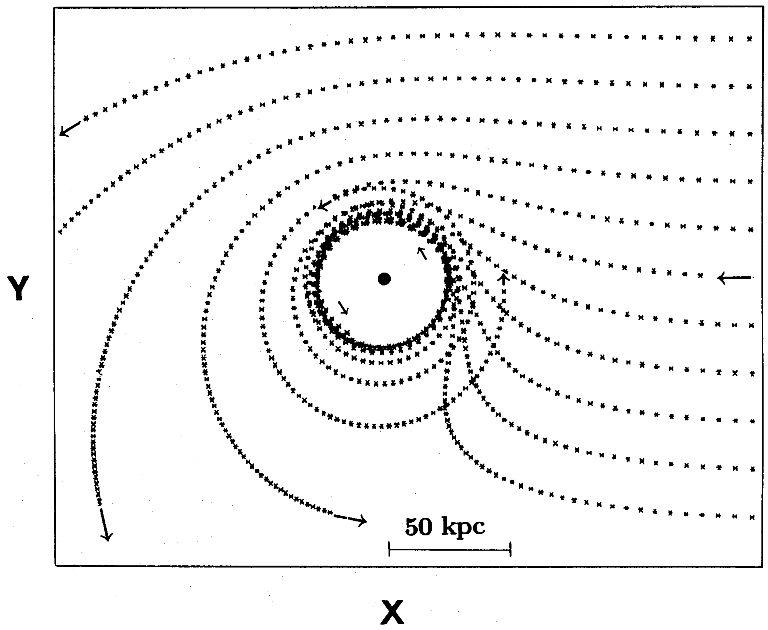

Fig. 1. Cloud orbits encountering a spiral galaxy within the x-y plane. The capture frequency is asymmetric with respect to the x-axis due to the rotation of the gas disk and halo. The galactic rotation is in the counter-clockwise direction. The injection speed of clouds is 400 km s^{-1} . The cloud positions are plotted by dots every 2×10^7 yr.

is also asymmetric about the x-axis, as is the case in figure 1. Conspicuous in this figure is that the retrograde clouds are rapidly accreted toward the central region, which occurs as follows: when a cloud crosses the galactic disk on the retrograde side, it feels a strong drag and loses kinetic energy as well as angular momentum. The orbit then changes to a semi-polar type, whereby the halo gas in the polar region rotates at a much slower velocity than the disk. After half a rotation in a few 10^8 yr, the cloud crosses the galactic plane from the bottom, and again loses angular momentum. In a few crossings of the disk in this way, the cloud loses almost all of its angular momentum and kinetic energy, and is attracted toward the nuclear region. The cloud is finally captured by the disk in the nuclear region.

We then consider the case in which a spiral galaxy experiences an encounter with an ensemble of many individual clouds. We simulate the motions of many (N) clouds which are initially distributed within a sphere of radius $R_N \sim 5$ kpc; we call these "N-clouds," and take $N \sim 200$. When the clouds encounter a galaxy within the x-y plane on direct orbits, they are stretched into a spiral, and are gradually accreted toward the galaxy. Finally, they form a one-armed, tightly wound spiral showing a ring feature. For head-on and retrograde encounters in the x-y plane, they are more rapidly accreted and form a ring of a smaller radius. In either case, however, no accretion toward the central region occurs, as is readily expected from figure 1.

However, a remarkable result is obtained for a *retrograde and off-plane encounter.* Figure 3 shows the result for a 45°retrograde encounter. The orbits of individual clouds greatly change when they cross the galactic plane, and finally attain semi-polar

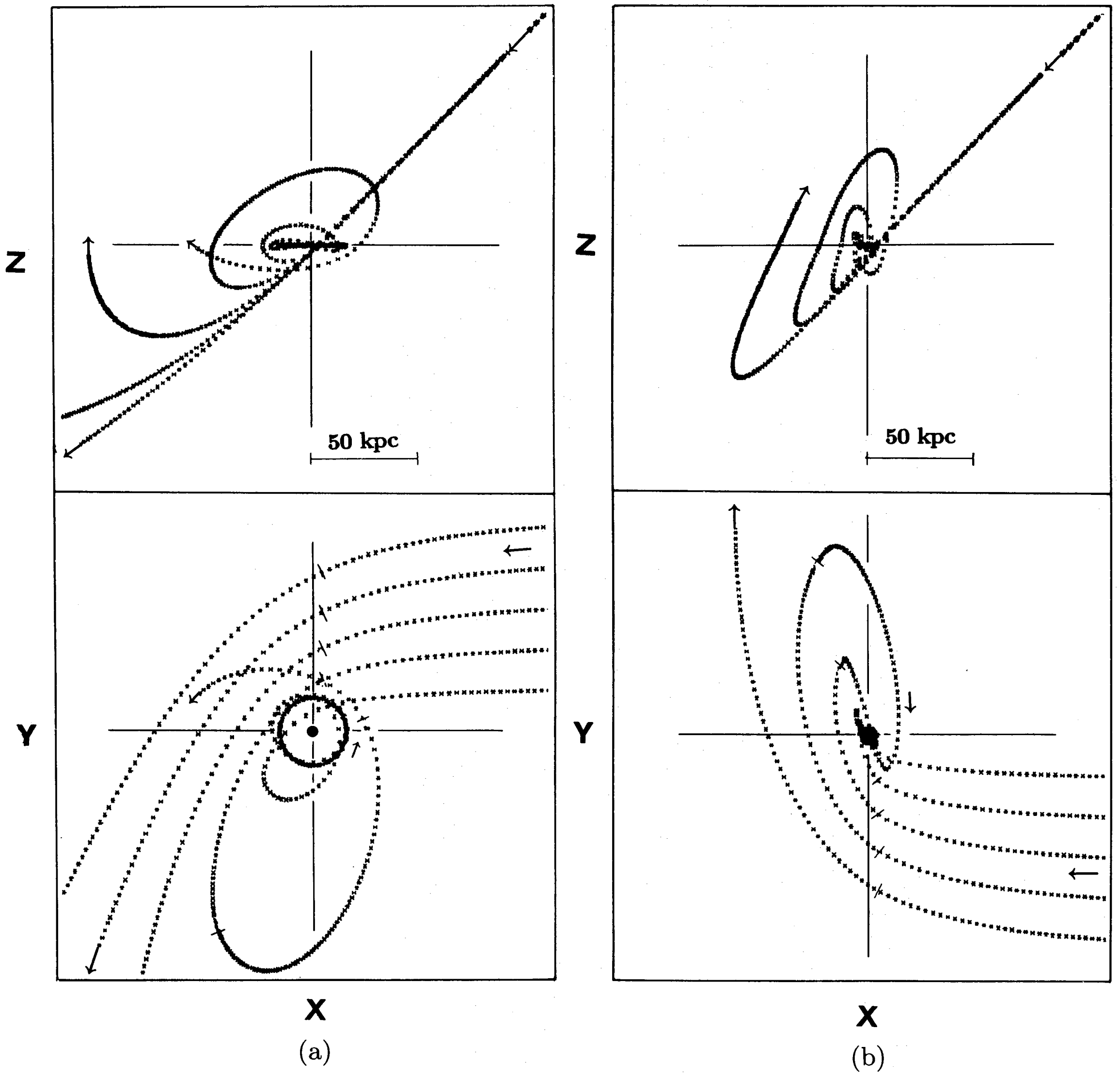

Fig. 2. Inclined hyperbolic orbits at an inclination angle of 45°and injection speed of 200 km s^{-1} : (a) Direct and (b) Retrograde encounters. The capture frequency is asymmetric. Note that the retrograde clouds are accreted toward the nucleus. The cloud positions are plotted by dots every 2×10^7 yr.

orbits. It is conspicuous that nearly all clouds are accreted toward the central few kiloparsecs, where they form a rotating disk of small radius. This accretion occurs for a wide range of injection angles, and for a wide range of impact velocities ($100 \sim 300$ km s^{-1}) and impact parameters ($\sim$ 10 to 100 kpc). Such accretion occurs even for parallel orbits to the galactic plane, provided that they are off-plane and retrograde (figure 4).

4. Discussion

From the simulation we conclude that if intergalactic clouds approach the galaxy

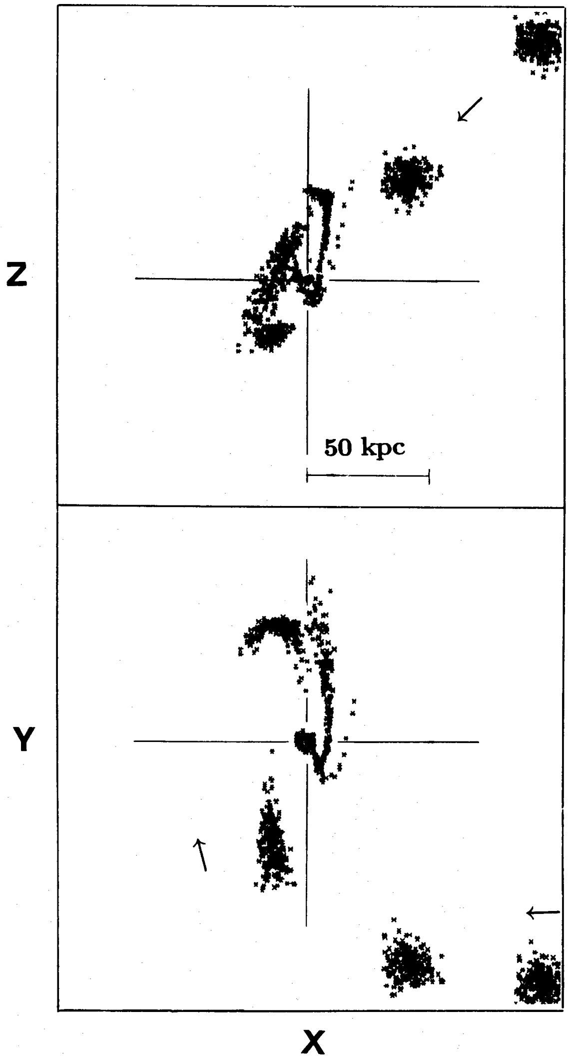

Fig. 3. Ram-pressure accretion of N-clouds for an inclined retrograde encounter at 45°at an injection speed of 141 km s^{-1} . Note that the clouds are accreted toward the nuclear region within a few rotations. The clouds are plotted every 5×10^8 yr.

on *off-plane orbits from the retrograde side*, either inclined or parallel to the galactic plane, the clouds are accreted toward the central region within one or two orbitings around the galaxy, or within a few 10^8 yr. The accreted clouds form rotating disk of a few kiloparsec radius.

The accretion of intergalactic gas clouds fuel the nuclear region and probably trigger starburst. Starburst triggered in this way must be sporadic and stochastic, depending on the frequency of "bombing." We stress that even if the bombing is random, which is more probable for intergalactic clouds, the clouds hit the nucleus rather accurately, provided that their orbits are retrograde and off-plane. An important aspect of the present result is that this accretion process applies to any galaxy, including isolated galaxies: Only clouds, or even fluctuations, in the intergalactic space, through which the galaxy is moving, are sufficient to fuel and cause starburst in the central

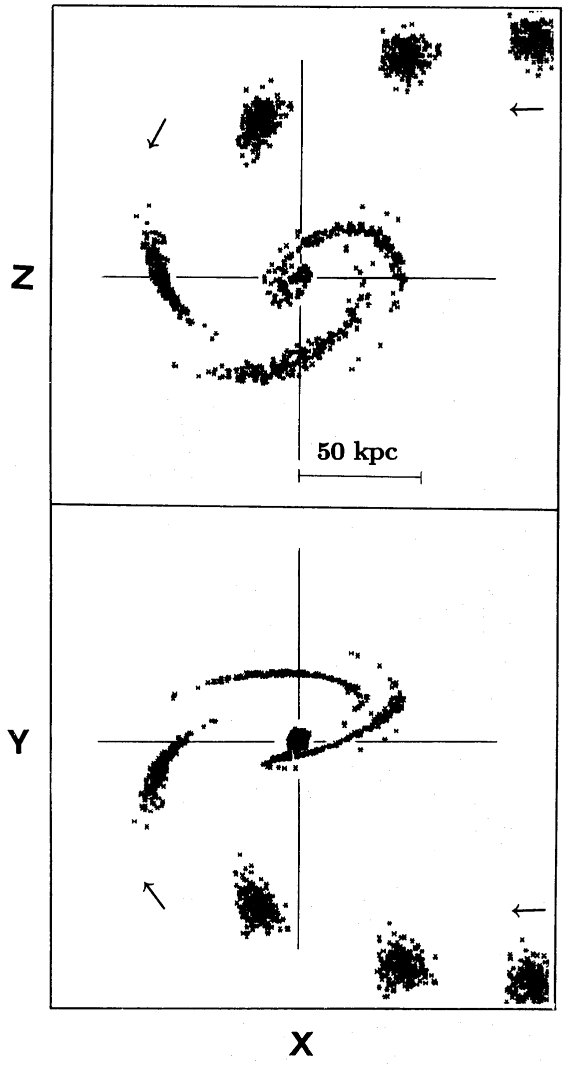

Fig. 4. Ram-pressure accretion of N-clouds by a rotating hot gas halo for a retrograde encounter parallel to, but off, the plane at an injection speed 100 km s^{-1} . Note that the clouds are accreted to the nuclear region. The clouds are plotted every 5×10^8 yr.

region.

Hence, this would hint at an answer to the long-standing question: why is starburst observed in some isolated galaxy?

We have assumed that the disk and halo gases have angular momentum that is sufficiently large compared to that of infalling clouds. However, if we take into account the finite amount of angular momentum, disk rotation should be significantly influenced. Since the capture frequency of retrograde clouds is much higher than direct ones, the accretion of clouds results in a loss of angular momentum of the gaseous components of the galaxy. As a consequence the galactic disk may contract, which would further enhance starburst.

Finally, we mention that the clouds infalling to the nuclear region must exhibit peculiar kinematics distinguished from disk rotation. For example, the apprent counter-rotation of gas observed in the spiral galaxy NGC 2217 (Bettoni et al. 1990) would be due to an accretion of external gas clouds. The numerous high-velocity H I clouds in our Galaxy would be circum galactic clouds (e.g., van Woerden et al. 1985). If some fraction of such clouds is accreted to the nuclear region, it would exhibit peculiar kinematics. This could explain the peculiar, and even counter-rotating, motions of some molecular clouds observed in our galactic center (Bally et al. 1987).

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References

Bally, J., Stark, A. A., Wilson, R. W., and Henkel, C. 1987, *Astrophys. J., Supple.*, **65**, 13.

Bettoni, D., Fasano, G., and Galletta, G. 1990, *Astron. J.*, **99**, 1789.

de Boer, K. S., and Savage, B. D. 1983, *Astrophys. J.*, **265**, 210.

Farouki, R., and Shapiro, S. L. 1980, *Astrophys. J.*, **241**, 928.

Gisler, G. R. 1979, *Astrophys. J.*, **228**, 385.

Gottesman, S. T., and Weliachew, L. 1977, *Astrophys. J.*, **211**, 47.

Gunn, J. E., and Gott, J. R., III. 1972, *Astrophys. J.*, **176**, 1.

Haynes, M. P., Giovanelli, R., and Roberts, M. S. 1979, *Astrophys. J.*, **229**, 83.

Hummel, E., Lesch, H., Wielebisnki, R., and Schlickeiser, R. 1988, *Astron. Astrophys.*, **197**, L29.

Mathewson, D. S., Ford, V. L., Schwarz, M. P., and Murray, J. D. 1979, in *The Large-Scale Characteristics of the Galaxy, IAU Symp. No. 84*, ed. W. B. Burton (Reidel Publishing Company, Dordrecht), p. 547.

Nagai, R., and Miyamoto, M. 1976, *Publ. Astron. Soc. Japan*, **28**, 1.

Noguchi, M. 1988, *Astron. Astrophys.*, **203**, 259.

Rieke, G. H., Lebofsky, M. J., Thompson, R. I., Low, F. J., and Tokunaga, A. T. 1980, *Astrophys. J.*, **238**, 24.

Sancisi, R., Thonnard, N., and Ekers, R. D. 1987, *Astrophys. J., Letters*, **315**, L39.

Sofue, Y., Reuter, H.-P, Krause, M., Wielebinski, R., and Nakai, N. 1991, submitted to *Astrophys. J., Letters.*

Sofue, Y., and Wakamatsu, K. 1991a, submitted to *Astrophys. J.*

Sofue, Y., and Wakamatsu, K. 1991b, submitted to *Publ. Astron. Soc. Japan, Letters.*

Tsuru, T., Ohashi, T., Makishima, K., Mihara, T., and Kondo, H. 1990, *Publ. Astron. Soc. Japan*, **42**, L75.

van Woerden, H., Schwarz, U. J., and Hulsbosch, A. N. M. 1985, in *The Milky Way Galaxy, IAU Symp. No. 106*, ed. H. van Woerden and R. J. Allen (Reidel Publishing Company, Dordrecht), p. 387.

Wakamatsu, K. 1990, *Astrophys. J.*, **348**, 448.

Weliachew, L., Sancisi, R., and Guélin, M. 1978, *Astron. Astrophys.*, **65**, 37.