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Shock Wave from a Galactic Nucleus into a Halo and Intergalactic Space

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Abstract

The propagation of a shock wave associated with an explosion at the nucleus of a disk galaxy through the halo and intergalactic gas is studied. An initially spherical shock front expands into the disk and halo, being elongated in the direction perpendicular to the disk plane. In the halo the front attains an Ω-shaped shell structure, which is observed as a large radio lobe in edge-on galaxies. We call attention to several galaxies in which such Ω-shaped radio lobes have been observed.

Key words: Galactic nucleus; Halo; Intergalactic gas; Shock waves.

1. Introduction

The propagation of shock waves associated with an active galactic nucleus has been extensively studied with particular reference to the formation of double radio sources (Sakashita 1971; Rees 1971; Scheuer 1974; Blandford and Rees 1974; Möllenhoff 1976; Sanders 1976; Witta 1978; Morita and Sakashita 1978). In the current shock wave theories such as those of Sakashita (1971) and Möllehnoff (1976), an exponential distribution or a Gaussian distribution of the gas density has been assumed in a spheroidal disk around the nucleus, which is surrounded by vacuum. However, it has been shown that in our Galaxy a hot gaseous corona of $\sim 10^6$ K and a density of $n=10^{-3}$–10^{-4} cm^{-3} exists and surrounds the galactic disk with a scale height of several kiloparsecs (Spitzer 1956; Savage and de Boer 1979).

If a strong blast shock wave associated with an explosion at the galactic center penetrates through such a halo of a finite gas density, the propagation will be different from that predicted for an exponential- or Gaussian-law disk in vacuum. Even if the disk is directly exposed to the intergalactic gas, the shock propagation would be much affected by the intergalactic gas. In the present paper we study the propagation of an initially spherical shock wave through a gaseous halo and the intergalactic gas after penetrating through a flat disk.

2. The Propagation of Shock Waves

Using the method of Laumbach and Probstein (1969), Sakashita (1971) has derived an

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equation for the time evolution of a shock envelope initiated by a point explosion in an adiabatic gas, assuming an axisymmetric density distribution. The flow field of the gas is assumed to be locally radial, and the heat transfer by radiation and counter-pressure are neglected. We here make use of this method. A detailed description of the method and its feasibility of the application to astrophysical problems are given in their paper.

For the background, an undisturbed density distribution of gas, we take the following form:

$$\rho_0(r,\theta)=\rho_c\left\{\exp\left[-\frac{r^2}{D^2}\Theta^2(\theta)\right]+h\right\}, \tag{1}$$

where (r, θ) are the polar coordinates, ρ_c is the central density, D is a characteristic length of the density distribution, and h is a constant small compared to unity. The first term represents the density profile in a spheroid whose oblateness is represented by the following equation (Möllenhoff 1976):

$$\Theta(\theta)=\left(1+\frac{e^2}{1-e^2}\cos^2\theta\right)^{1/2}, \tag{2}$$

where e is the eccentricity of the isodensity surface of the spheroid. The second term in equation (1) represents a halo component and/or an intergalactic gas with a constant density.

Following Möllenhoff (1976) we introduce a dimensionless reduced radius

$$y=r\Theta/D \tag{3}$$

and a reduced time

$$x=\left(\frac{E\Theta^5}{4\pi\rho_c D^5}\right)^{1/2}t, \tag{4}$$

where t and E are the real time and the explosion energy, respectively. Then Sakashita's (1971) equation can be written in the form

$$y''=\frac{y'^2}{7}\left[\frac{2ye^{-y^2}}{h+e^{-y^2}}-\frac{11}{2y}-\frac{4y^2}{K}(h+e^{-y^2})\right]+\frac{32}{21yK} \tag{5}$$

for an adiabatic exponent $\gamma=5/3$, where

$$K=\int_0^y (e^{-u^2}+h)\,u^2du\,. \tag{6}$$

The prime means differentiation with the reduced time x.

Before integrating numerically, we obtain asymptotic solutions for $y\ll1$ and $\gg1$. When $y\ll1$, we have (Möllenhoff 1976)

$$y=(200/9)^{1/5}x^{2/5} \tag{7}$$

and

$$y'=(32/9)^{1/2}y^{-3/2}\,. \tag{8}$$

We use these solutions as the initial condition for the numerical integration. Equations (7) and (8) coincide with Sedov's (1959) similarity solution in a uniform adiabatic gas for a strong point explosion. At a sufficiently large radius, $y^3h\gg1$, where the first term in equation (6) becomes negligible compared to the second, we have $y \propto x^{2/5}$ and $y' \propto y^{-3/2}$. Therefore the solution tends again to Sedov's (1959) similarity solution in a uniform medium, but with a lower density by a factor of h, or $h\rho_c$ instead of ρ_c.

On the other hand, if the galaxy is surrounded by vacuum, or $h=0$, the asymptotic solution at $y \gg 1$ yields

$$x = A\int_0^y e^{-(1/7)u^2} du = A\sqrt{7\pi}/2 \tag{9}$$

and

$$y' = \frac{1}{A} e^{(1/7)y^2}, \tag{10}$$

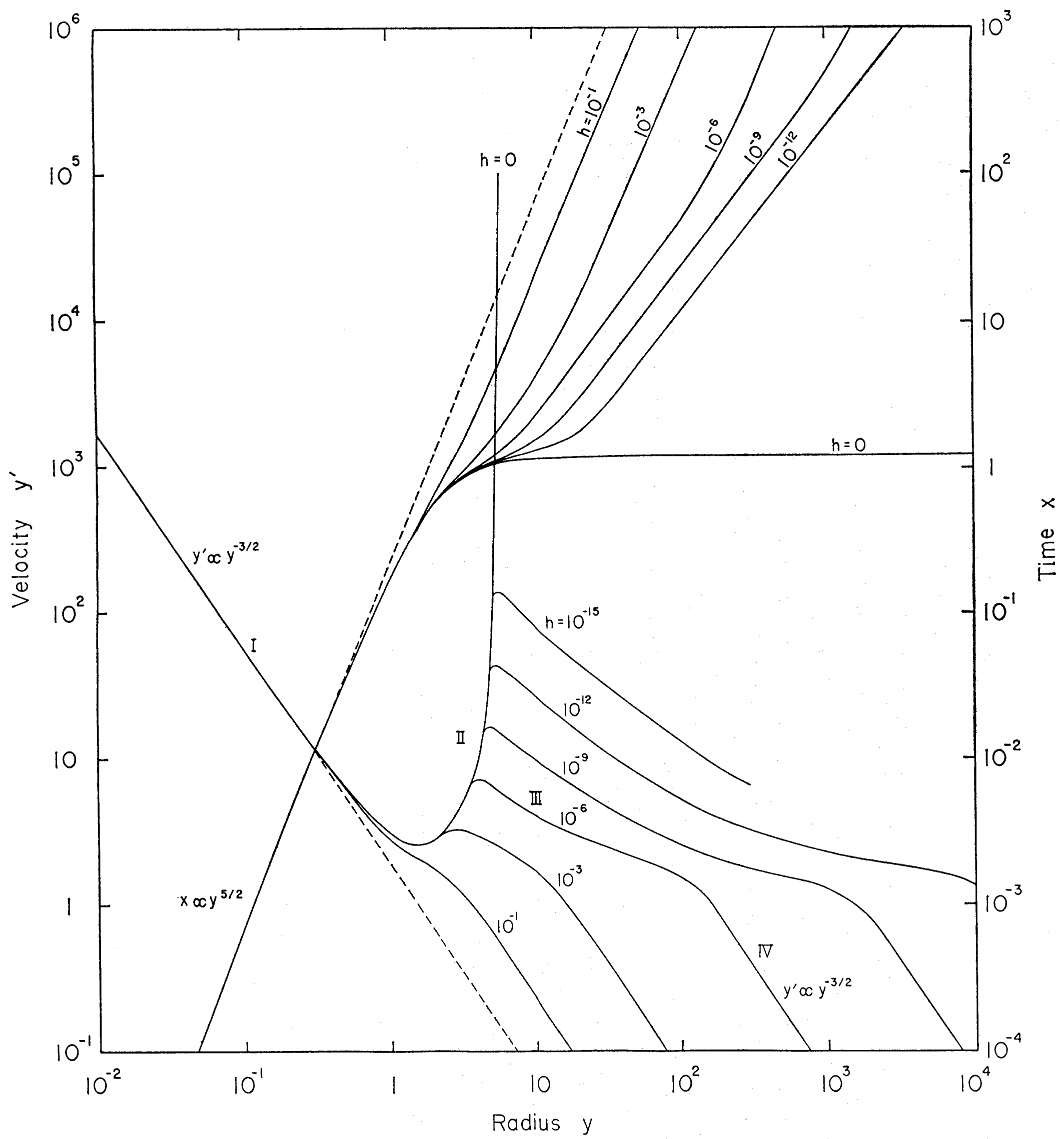

Fig. 1. The dimensionless reduced velocity y' of the shock front and reduced time x elapsed from the explosion as functions of the reduced radius y for the solutions of equation (5). The ratios of the halo density to the central density is taken as $h=0.1$ to 10^{-15}. See the text for the explanation of Phases I–IV on the line of $h=10^{-6}$.

where A is a constant of integration. From these equations we know immediately that the velocity y' increases to infinity within a finite time and the radius becomes infinity. This is the so-called "break-through" of the spheroid, which Sakashita (1971) and Möllenhoff (1976) have considered to be the cause of high-speed jets.

3. Formation of an Ω-shaped Shock Envelope

(i) Explosion in a Disk of a Gaussian-law Density Distribution with a Uniform Density Halo

Figure 1 shows the numerical solutions of equation (5) for various values of h from $h=0.1$ to 10^{-15}, where the reduced velocity y' and the reduced time x are plotted as functions of the reduced radius y. At small y the curves represent equations (7) and (8), and the shock is approximated by that of a strong point explosion in a homogeneous gas. We refer to this stage as Phase I. With increasing radius, the shock penetrates into a region of a steeply decreasing density, where the shock velocity is accelerated because of the decrease in the external density. Consequently the velocity y' starts to increase (Phase II). When $h=0$, or the system is surrounded by vacuum, the solution tends to that given by equations (9) and (10), and the breakthrough occurs at around $y=6$. This result agrees with that of Möllenhoff (1976).

However, if there exists a uniform halo of finite h ($\neq 0$), the shock suffers again from a strong deceleration in the halo. This begins when $e^{-y^2} \approx h$, and afterwards the velocity again decreases (Phase III). In this stage the internal energy of the accelerated gas in Phase II remains large enough and the pressure term is still larger than the momentum term in equation (5), so that the shock velocity decreases not so fast as in Phase I. This

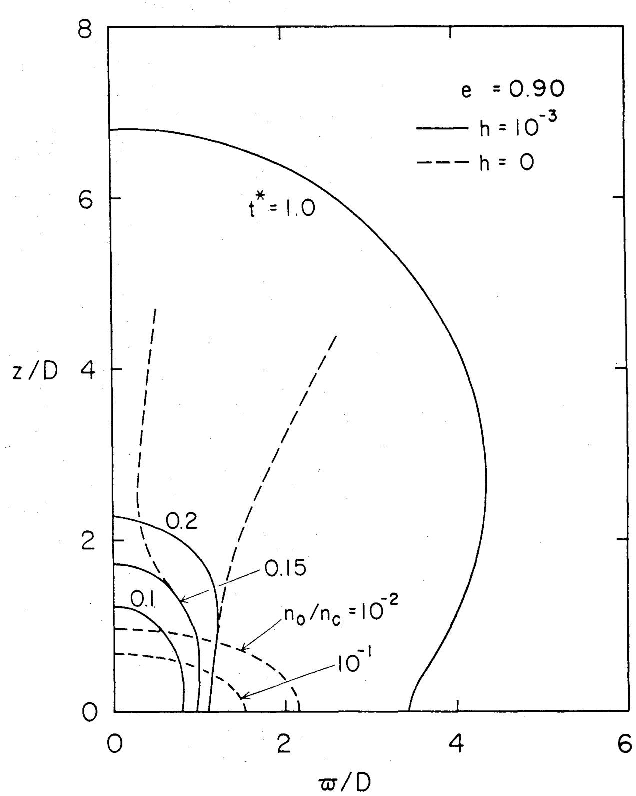

Fig. 2. Shock envelope in the case of $e=0.9$ on the ϖ-z plane. The length is normalized by D, the scale radius of the Gaussian-law disk. The halo density is taken as $h=10^{-3}$ (solid lines) and $h=0$ (dashed lines).

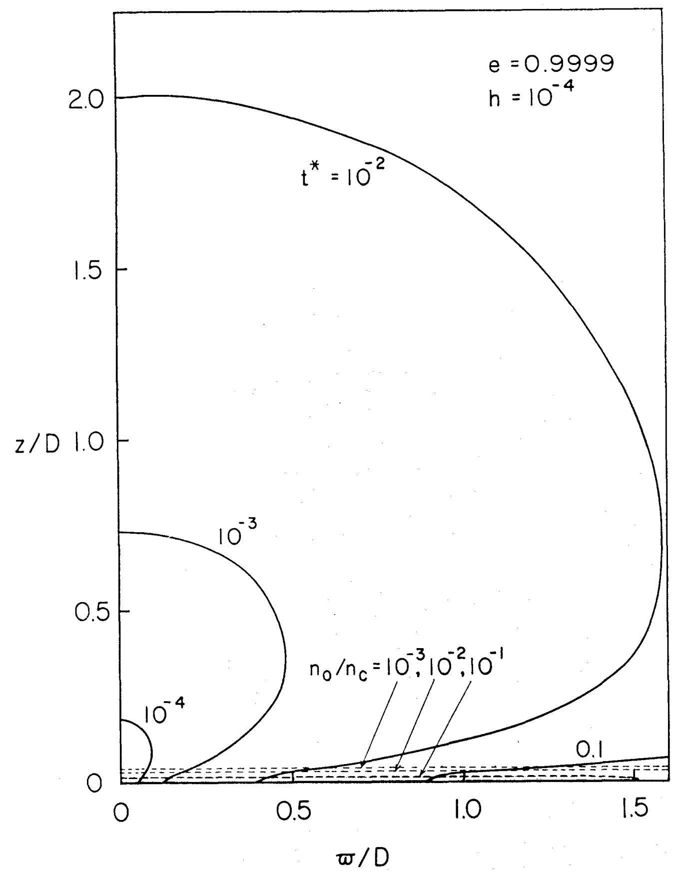

Fig. 3. The same as figure 2 but for $e=0.9999$ and $h=10^{-4}$.

stage lasts until $y \approx h^{-y^3}$, at which the mass of the swept-up gas from the halo becomes comparable to that of the blown-off gas from the disk. As the shock envelope expands further and the mass of the swept-up gas from the halo becomes dominant, the momentum term becomes again important. The shock wave is then expressed again by Sedov's (1959) solution (Phase IV) as in equations (9) and (10) with the ambient density $h\rho_c$ instead of ρ_c. The four stages, Phases I–IV, are indicated in figure 1. We emphasize that the break through does not occur, unless h is extremely small. Indeed, even if the halo density is as low as $h=10^{-15}$, the expansion velocity attains a maximum of $y' \approx 100$ at $y \approx 5$ and is then decelerated, finally tending to decrease as $y' \propto y^{-3/2}$.

To see the time evolution of the shock envelope with respect to the real time t, the reduced time x is deduced from equation (4). The corresponding value of y can be obtained from figure 1 and transformed to the real location r by equation (3). Figures 2 and 3 show the time evolution of the shock envelope thus obtained on the ϖ-z plane for several values of eccentricity e and halo density h, where $\varpi = r \sin\theta$ and $z = r \cos\theta$. The time is reckoned in units of $(4\pi\rho_c D^5/E)^{1/2}$.

For $e=0.9$ and $h=0$ we obtain the same result as that of Möllenhoff (1976). However, if the halo density is finite, the envelope is only elongated in the z-direction and expands into the halo almost spherically, and the envelope becomes omega (Ω)-shaped. Figure 2 shows the envelope for $h=10^{-3}$. Even for a smaller halo density, say $h=10^{-6}$, we have a similar envelope shape. For flatter disks of $e=0.99$ and $e=0.9999$, we have also Ω-shaped shock envelopes. Figure 3 shows the result for $e=0.9999$ and $h=10^{-4}$. We may here recall that a similar Ω-shaped wave front has been obtained for the propagation

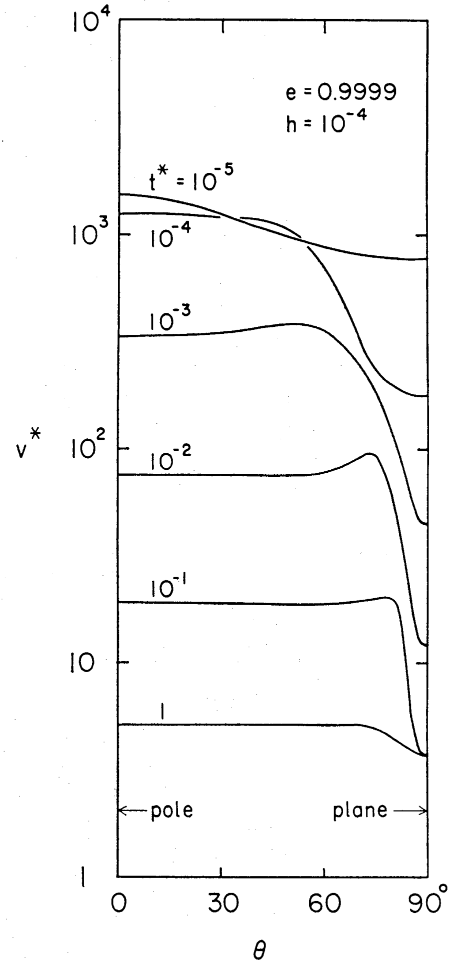

Fig. 4. Shock velocity as a function of θ in the case of $h=10^{-4}$ and $e=0.9999$ (the same as in figure 3).

of an MHD wave which expands from the nucleus into a magnetoionic halo with a constant Alfvén velocity (Sofue 1977, 1980). To see how the expansion velocity of the shock front depends on the direction θ, in figure 4 we plot $v^*=v(E/4\pi\rho_c D^3)^{-1/2}$ as a function of θ at several epochs. The time t^* in the figure is defined by $t^*=t(4\pi\rho_c D^5/E)^{-1/2}$. The parameter combination is the same as in figure 3.

(*ii*) *Explosion in a Gaussian-Law Disk with an Exponential-Law Halo and the Uniform Intergalactic Gas*

In spiral galaxies like ours the halo density will decrease exponentially with height z from the galactic plane with a scale height much larger than the disk thickness. At large distances it will merge into the intergalactic gas smoothly. To simulate such a galaxy, we take the following density distribution:

$$\rho_0=\rho_c[\exp(-r^2\Theta^2/D^2)+g\exp(-r\Theta/H)+h]\,, \tag{11}$$

where the first term represents the Gaussian density distribution in the disk, the second the exponential density decrease in the halo, and the third represents the intergalactic gas. The constant g is taken small compared to unity. The scale height H is taken to be larger than D and the constant term h is much smaller than g.

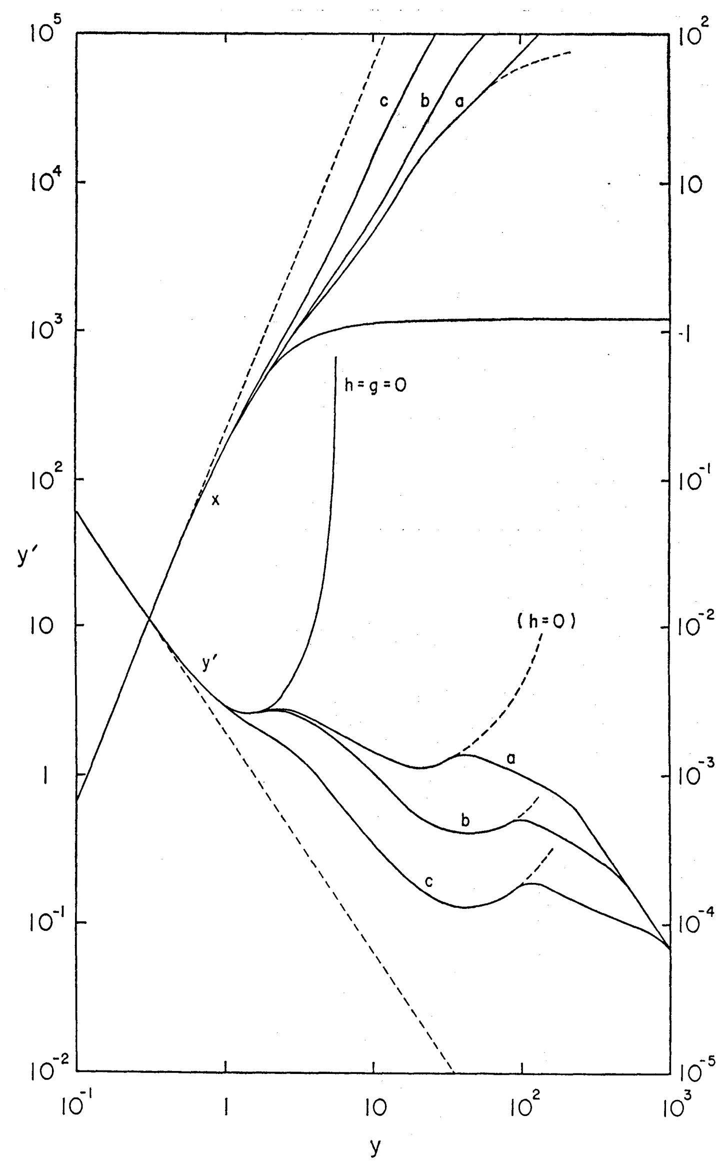

Fig. 5. The same as figure 1 but for a halo with an exponentially decreasing density and an intergalactic gas of $h=10^{-6}$: (a) $g=10^{-2}$ and $H=5D$; (b) $g=10^{-2}$ and $H=10D$; and (c) $g=0.1$ and $H=10D$.

Computations were carried out for several combinations of the parameters. The results are shown in figure 5. The same form of the oblateness has been assumed both for the disk and halo components for computational convenience, because we are interested only in the shock envelope at $\varpi \lesssim D$, where the density profile is almost plane parallel. The result for $g=10^{-2}$, $h=10^{-6}$, and $H=5D$ (line a in figure 5), for example, shows that the shock velocity varies with y in the same way as in figure 1 until $y \cong 2$. The velocity reaches a maximum as early as $y \cong 2.4$ and then is decelerated due to the halo. With increasing y at $y \gtrsim 10$ the shock envelope again undergoes acceleration due to the exponential decrease of the density. If there exists no intergalactic gas ($h=0$), the shock velocity increases steeply to infinity, which was already shown by Sakashita (1971). However, if the intergalactic gas does exist, the shock suffers from strong deceleration and the velocity starts to decrease at $y \approx 50$. Finally, when the swept-up mass from the intergalactic gas becomes dominant,

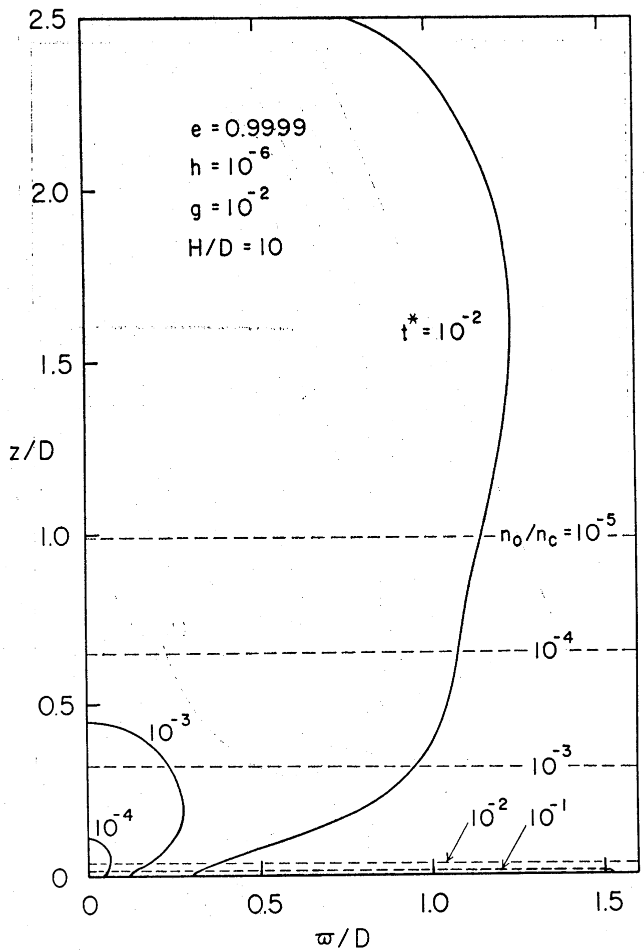

Fig. 6. Shock envelope for $e=0.9999$ with a halo of an exponentially decreasing density and an intergalactic gas of a constant density: $h=10^{-6}$, $g=10^{-2}$, and $H=10D$ (the same as line b in figure 5).

the solution tends again to Sedov's (1959) similarity solution, which occurs at $y\sim 200$.

The time evolution of the shock envelope is shown in figure 6 for $e=0.9999$. The parameter combination here is $h=10^{-6}$, $g=10^{-2}$, and $H=10D$ (line b in figure 5). The shock envelope is similar to that in figure 3, but is more elongated in the z-direction. The larger elongation is due to the exponential decrease of the halo density. The second acceleration at around $y\approx 40$ in figure 5 (line b) corresponds to the hump at a height of $z=0.3D$ at $t^*=10^{-2}$ in figure 6.

We here apply the present model to a galaxy with a realistic combination of parameters. We consider the case of $D=7$ kpc, $H=10D$, $e=0.9999$, $g=0.1$, $h=10^{-6}$ and the central density of $n_c=\rho_c/m_H=3\ \mathrm{cm}^{-3}$. The explosion energy at the galactic center is taken to be $E=2.6\times 10^{56}$ erg, which is close to the energy estimated for the nuclear activity in a spiral galaxy by Oort (1977). The calculated shock envelope for these parameters is given in figure 7.

At $t^*=10^{-5}$ ($t=3\times 10^4$ yr after explosion), the velocity is almost constant over the shock envelope at $v=2000\ \mathrm{km\ s^{-1}}$ and the shock radius is 140 pc. At $t=3\times 10^6$ yr ($t^*=0.001$) the velocity decreases to $80\ \mathrm{km\ s^{-1}}$ in the galactic plane and to $400\ \mathrm{km\ s^{-1}}$ in the halo. The shock front of this eopch is at $\varpi\approx 1$ kpc in the galactic plane and $z\approx 5$ kpc in the halo on the z-axis. The shock envelope has an Ω shape elongated in the z-direction.

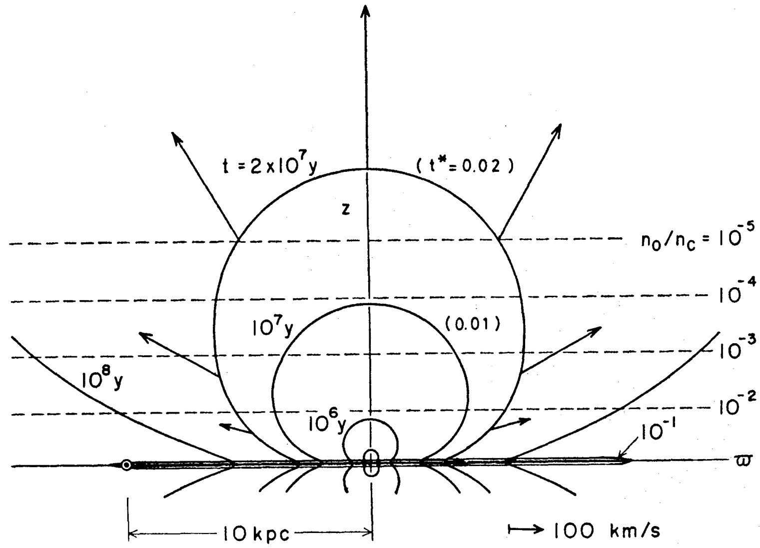

Fig. 7. Shock envelopes for a case with a halo of an exponentially decreasing density and an intergalactic gas with $h=10^{-6}$, $g=0.1$, and $H=10D$. The indicated distance, time, and velocity are for a shock wave in a realistic disk galaxy with $D=7$ kpc, $n_c=3\ \mathrm{cm}^{-3}$, and $E=2.6\times10^{56}$ erg.

After 3×10^7 yr ($t^*=0.01$) the shock envelope with an expansion velocity of 160 km s^{-1} becomes nearly spherical at $r=13$ kpc except near the galactic plane, where the expansion velocity has already decreased to 30 km s^{-1} at $\varpi\approx3$ kpc. For stronger explosion energy, say $E=10^{60}$ erg, which is often quoted for elliptical galaxies and quasars, we have velocities 300 times the above values and the time scale is reduced by a factor of 0.01 with the same radius scale.

In the case of $E\cong10^{56}$ erg the gas temperature behind the shock front in the halo at $t=3\times10^6$ yr and $r=5$ kpc is about 10^7 K corresponding to the expansion velocity of 400 km s^{-1}. Since the temperature of the undisturbed halo is of the order of 10^{5-6} K, the shock is still strong enough. If the halo gas density is $n=10^{-3}\ \mathrm{cm}^{-3}$, the cooling time in the shocked region is about 10^8 yr, which is large compared with the time scale of the shock evolution. Thus we may argue that the assumption of the adiabatic gas approximation is good enough.

3. Discussion

We have shown that a point explosion at the nucleus of a disk galaxy with a halo of a finite density results in an Ω-shaped shock envelope in the halo. The breakthrough of the disk resulting in a very high-speed jet is shown to be difficult to occur unless the halo density is much smaller than $h=10^{-15}$.

Below we call attention to some observational results which show Ω-shaped radio lobe structures in edge-on galaxies. They may be interpreted with the present model of shock waves from their nuclei.

NGC 3079: The 21-cm continuum map by de Bruyn (1977) of this almost edge-on galaxy exhibits two spurs perpendicular to the major axis at symmetrically opposite positions with respect to the galaxy center. The spurs could possibly have a similar structure to the Ω-shaped shock envelope in the present model (figure 8). Recent VLA maps of the inner region of NGC 3079 have shown Ω-shaped lobes emerging from the center perpendic-

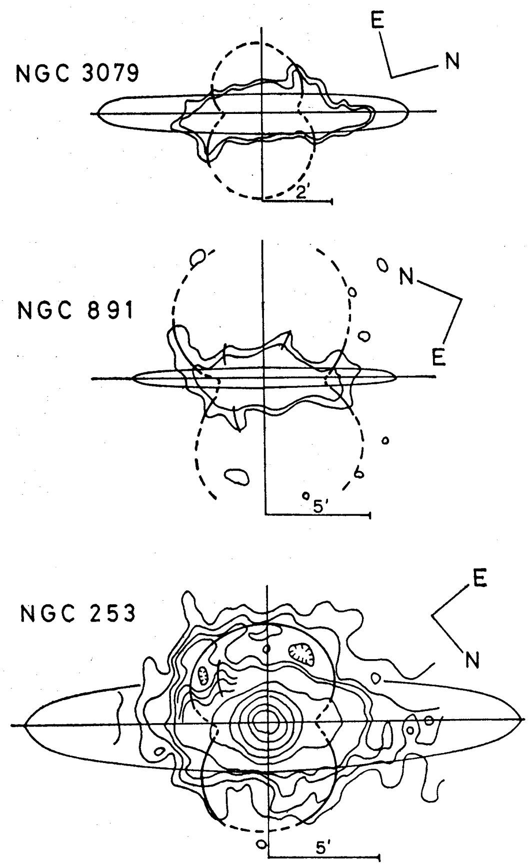

Fig. 8. Possible interpretation by the present model for the radio spur and loop structures in galaxies, NGC 3079, NGC 891, and NGC 253. The contour lines are from radio observations by de Bruyn (1977) and Beck et al. (1979). Oblate ellipses indicate approximate outlines of the optical disks. Possible expected envelopes of shock waves from the nuclei are indicated.

ular to the disk (Duric et al. 1983). The lobe could possibly be due to a shock wave from the nucleus into the halo.

NGC 891: This is an edge-on galaxy having a halo component in the radio continuum (Allen et al. 1978; Beck et al. 1979). The 8.7-GHz map by Beck et al. (1979) exhibits some radio spurs similar to those in NGC 3079, which could be part of an Ω-shaped shock envelope.

NGC 253: This is an irregular spiral of large inclination. The 8.7-GHz map of Beck et al. (1979) reveals a quasi-spheroidal halo extending up to 6 kpc from the center. It is remarkable that the southern halo has a concentric loop structure with the galaxy center. The northern halo is somewhat weaker, but we can still recognize two radio spurs symmetric to the ridges of the southern loop with respect to the major axis. The loop structure may be evidence for an Ω-shaped shock envelope with a radius of 4′ or 4 kpc at a 3.5-Mpc distance of the galaxy. In figure 8 we illustrate the radio ridges and loop.

In addition to these galaxies we note that a nonthermal radio halo has been found in NGC 4631, an edge-on galaxy (Ekers and Sancisi 1977; Wielebinski and von Kap-Herr 1977), which shows also a possible indication of radio spurs, although very faint, and may be due to an old shock front produced by a nuclear explosion.

The galactic center lobe: Sofue and Handa (1984) and Sofue et al. (1984) report the

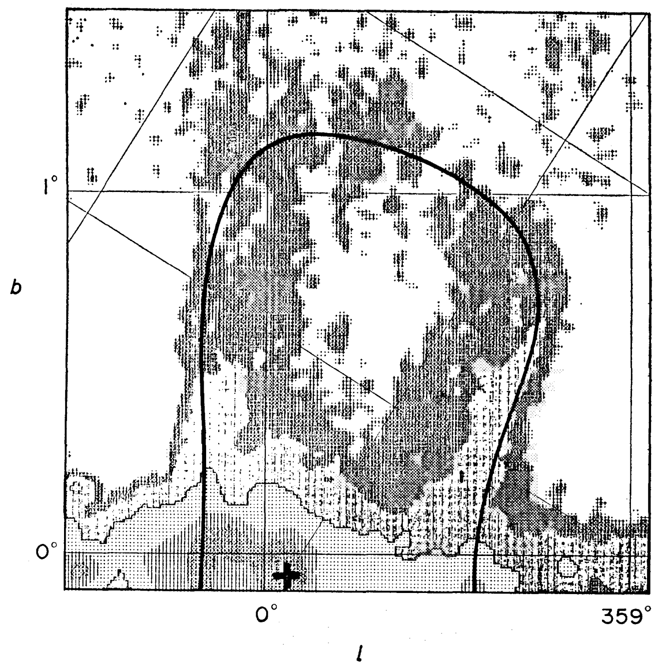

Fig. 9. The galactic center lobe found at 10 GHz in gray scale [see Sofue and Handa (1984) for details]. A possible shock envelope as suggested from the present model is indicated with a thick line.

existence of an Ω-shaped radio lobe over our galactic center with a diameter of $\sim$200 pc. The lobe extends towards positive galactic latitude almost perpendicularly to the galaxy disk. The cross section across the lobe suggests a shock-compressed shell structure. The shape of the lobe resembles well the front shape at $t^*=0.2$ in figure 2. We here discuss a possibility that the lobe is an Ω-shaped shock envelope as calculated in this paper (figure 9).

The nuclear disk of our Galaxy has a half thickness of $\sim$100 pc and a radius $\sim$200–300 pc with a gas density of about $10m_{\rm H}\,{\rm cm}^{-3}$ (Mezger and Pauls 1979). The disk may be roughly expressed by a Gaussian-law disk of $e=0.9$ and $D=230$ pc model of figure 2. If the lobe is a shock envelope at $t^*=0.2$ in the figure, we can estimate the explosion energy and the age by using figure 1, which yields $v(E/4\pi\rho_{\rm c}D^3)^{-1/2}\approx 3$. Preliminary CO line observations of the lobe region with a 4-m millimeter-wave telescope at Nagoya University show a high-velocity ($V_{\rm LSR}\approx 100\,{\rm km\,s}^{-1}$) CO gas associated with the lobe ridges (I. Sawa, private communication). If we adopt an expansion velocity of this order, $v\approx 100\,{\rm km\,s}^{-1}$, $\rho_{\rm c}=10m_{\rm H}\,{\rm cm}^{-3}$, and $D\approx 230$ pc, we obtain $E\sim 10^{54}$ erg. This explosion energy agrees well with that expected for the nuclear activity in a spiral galaxy by Oort (1977). The age of the lobe is then estimated to be 2×10^6 yr. The north-south asymmetry of the observed lobe remains as a question.

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