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Propagation of Magnetohydrodynamic Waves from the Active Galactic Center and Their Convergence into the 3-kpc Arm

Yoshiaki SOFUE

Department of Physics, Nagoya University, Chikusa, Nagoya

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Abstract

Magnetohydrodynamic (MHD) disturbances originating at the nucleus of the Galaxy propagate through the halo, and focus on a ring in the gaseous disk. An efficient ($\gtrsim$90 percent) convergence of the MHD waves into the ring is suggested as a possible mechanism to drive the 3-kpc arm expansion. The disk gas between the center and the 3-kpc arm is shown to remain undisturbed.

Key words: Galactic halo; Galactic nucleus; Magnetohydrodynamic waves; 3-kpc arm.

1. *Introduction*

The "3-kpc arm" observed at the λ 21-cm neutral hydrogen emission at a radius $\varpi=3.5$ kpc from the galactic center (ROUGOOR and OORT 1960; ROUGOOR 1964) has been investigated theoretically in two ways: one in relation to explosive events at the galactic nucleus (VAN DER KRUIT 1971; LYNDEN-BELL and REES 1971; SANDERS and PRENDERGAST 1974), and the other in relation to a dispersion ring at the inner Lindblad resonance of the spiral density waves (LINDBLAD 1964; LIN and SHU 1964, 1967; SIMONSON and MADER 1973).

VAN DER KRUIT (1971) has attempted to explain the arm as a dynamical counterpart of an explosion of the nucleus. He has considered that gas clouds were expelled from the nucleus with an initial velocity of some 600 km s^{-1} at a narrow angle of 25-30° to the galactic plane. After some 10^7-yr travel, they return to the gaseous disk at $\varpi\approx3.5$ kpc and drive the expanding motion of $v_\varpi=53$ km s^{-1}. In his model, however, the calculated rotation velocity of the clouds, $v_\theta=150$ km s^{-1}, is somewhat lower than the observed value, $v_\theta=210$ km s^{-1}. Recently, SANDERS and PRENDERGAST (1974) have shown by their fully hydrodynamical treatment that an explosion with an expanding velocity as high as 3000 km s^{-1} at the galactic nucleus produces an oscillating ring around $\varpi\approx3$ kpc, in which the observed velocities are well reproduced. Their computation shows, however, that the gaseous disk in the central region is so violently disturbed that the disk is almost completely disrupted. On the contrary, observations of neutral hydrogen gas have revealed the existence of a rather quiet nuclear disk, where the velocity dispersion is reported to be of the order of 20 km s^{-1} at $\varpi=300$-500 pc (SANDERS and WRIXON 1973).

In the present paper, standing on the explosion hypothesis, we propose a possible mechanism to produce a ring-like structure in the galactic disk through a convergence of magnetohydrodynamic (MHD) waves emitted isotropically from the active galactic center.

2. *MHD Wave Propagation through the Galactic Corona*

UCHIDA (1968, 1970, 1974) and UCHIDA, ALTSCHULER, and NEWKIRK (1973) have established a method to trace MHD wave packets in a magnetized plasma. They have applied the method to a "diagnosis" of coronal magnetic structure of the sun, using flare-associated fast-mode MHD wave fronts. They consider that the observed Moreton waves (MORETON 1960; UCHIDA 1968) are re-entry fronts of the MHD waves onto the chromosphere. In the present paper, we apply the method to the galactic disk and galactic corona in the central region of the Galaxy, and follow the behavior of the MHD waves originated at the galactic center.

When the square of the Alfvén velocity, V^2, is sufficiently greater than that of the sound velocity, a^2, the propagation of the fast-mode MHD wave packet is described by the following set of equations for an axisymmetric case (UCHIDA 1970):

$$\frac{dr}{dt}=\frac{\partial\mathscr{H}}{\partial p_r}\,, \tag{1}$$

$$\frac{d\theta}{dt}=\frac{\partial\mathscr{H}}{r\partial p_\theta}\,, \tag{2}$$

$$\frac{dp_r}{dt}=-\frac{\partial\mathscr{H}}{\partial r}+\frac{p_\theta}{r}\frac{\partial\mathscr{H}}{\partial p_\theta}\,, \tag{3}$$

$$\frac{dp_\theta}{dt}=-\frac{\partial\mathscr{H}}{r\partial\theta}-\frac{p_\theta}{r}\frac{\partial\mathscr{H}}{\partial p_r}\,, \tag{4}$$

and

$$\mathscr{H}=V(r,\theta)(p_r{}^2+p_\theta{}^2)^{1/2}\,, \tag{5}$$

where $(p_r, p_\theta)=\mathrm{grad}\,\Phi$, $p=|\mathrm{grad}\,\Phi|$, and $\Phi(r,\theta,t)$ is the phase function or the eikonal of the wave packet when the velocity of medium at the wave front is expressed as $\boldsymbol{v}=\hat{\boldsymbol{v}}\exp i\Phi$ with a slowly varying amplitude $\hat{\boldsymbol{v}}$. Here r and θ are coordinates of the wave packet and denote, respectively, the radius and the angle with the z-axis which is chosen to coincide with the galactic rotation axis.

The assumption that the Alfvén velocity is large enough compared with the sound velocity is rational in the galactic corona, too, in view of the following points.

The Alfvén velocity is given by $V=(2p_{\rm m}/\rho)^{1/2}$, where $p_{\rm m}$ and ρ are the magnetic pressure and gas density, respectively. We assume that $p_{\rm m}$ and ρ vary with z as $p_{\rm m}\propto\exp(-z^2/h_{\rm m}{}^2)$ and $\rho\propto\exp(-z^2/h_{\rm g}{}^2)$, where $h_{\rm m}$ and $h_{\rm g}$ are scale thicknesses of distributions of the magnetic pressure and gas density. Although most of the magnetic fields are frozen in the gas, a small portion of the fields may permeate into the halo enhanced by the Parker-type instability. The magnetic scale thickness is therefore considered to be somewhat greater than the gaseous one: we have $h_{\rm m}=(1+\varepsilon)h_{\rm g}$ with $0<\varepsilon\ll1$. Consequently, the Alfvén velocity may be written as

$$V=V_0\exp(z/H)^2 \tag{6}$$

with $H=h_{\rm g}/\varepsilon^{1/2}$, which denotes the typical scale of the z-variation of the Alfvén velocity. Here $z=r\cos\theta$, and V_0 is the Alfvén velocity at the galactic plane.

JACKSON and KELLMAN (1974) have shown that, in order to maintain an observed thickness of the gas disk against the z-directional gravitation, an equivalent turbulent velocity, v_{eq}, is required to be 10-20 km s^{-1} at ϖ=10-3 kpc. Extrapolating their data to $\varpi\cong 1$ kpc, we obtain $v_{eq}\approx 30$ km s^{-1} at ϖ=1-3 kpc, which we shall adopt below. On the other hand, the sound velocity, a, is 1 km s^{-1} in the H I gas, and amounts at most to 10 km s^{-1} even in the ionized interstellar gas. The velocity dispersion at the 3-kpc arm region is also observed to be 10 km s^{-1} (ROUGOOR 1964), which is too small to support the observed z-spread of the gas disk. Hence the z-spread must be supported by magnetic and/or cosmic-ray pressures. Then we have $(1/2)\rho v_{eq}^2 \cong p_m + p_{cr}$, where p_{cr} is the cosmic-ray pressure. Assuming equipartition between p_m and p_{cr}, we obtain that $V_0=(2p_m/\rho)^{1/2}\approx v_{eq}/2^{1/2}\approx 20$ km s^{-1}.

Taking account of equation (6), the requirement $V^2 \gg a^2$ is thus satisfied in the circumstance under consideration. This will be the case also in the nuclear disk closer to the galactic center ($\varpi\lesssim 500$ pc), where the velocity dispersion is observed to be 20 km s^{-1}, while the z-spread of the gas requires an equivalent turbulent velocity of the order of 100 km s^{-1} (SANDERS and WRIXON 1973).

We assume, for simplicity, an axisymmetry around the rotation axis, and stratified distributions parallel to the galactic plane for the gas density and magnetic field strength, and V_0 as well as H to be constant with ϖ. The non-dimensional basic equations are then written as

$$\frac{1}{\mathscr{F}}\frac{d\xi}{d\tau}=\frac{p_r}{p}, \tag{7}$$

$$\frac{1}{\mathscr{F}}\frac{d\theta}{d\tau}=\frac{p_\theta}{\xi p}, \tag{8}$$

$$\frac{1}{\mathscr{F}}\frac{dp_r}{d\tau}=-p\frac{\partial \ln\mathscr{F}}{\partial\xi}+\frac{p_\theta^2}{p\xi}, \tag{9}$$

and

$$\frac{1}{\mathscr{F}}\frac{dp_\theta}{d\tau}=-\frac{p}{\xi}\frac{\partial \ln\mathscr{F}}{\partial\theta}-\frac{p_r p_\theta}{p\xi}, \tag{10}$$

with $\xi=r/H$, $\tau=t/(H/V_0)$, $\mathscr{F}=\exp\zeta^2=V/V_0$, $\zeta=\xi\cos\theta$, and $p=(p_r{}^2+p_\theta{}^2)^{1/2}$.

3. *MHD Wave Fronts Focusing on a Ring; the 3-kpc Arm*

Numerical integrations were made of equations (7)-(10) using the Runge-Kutta-Gill method. Some initial locations for a source point of the MHD disturbances were given on the z-axis at $z=z_0$=0, 0.1, 0.25, 0.5, and $1H$. At the initial epoch (t=0), wave packets were isotropically emitted from the source point.

Figure 1 gives the result for the case that the source point is located exactly at the galactic center, $z_0=0$. In the early stage of propagation, ray-paths of the packets are radial and the wave front expands spherically. Then the surface is elongated in the z-direction and gradually refracted toward the galactic plane. After the packets travel a path length of about $2H$, they converge into a "focal ring" at $\varpi\cong 2H$. If we take H to be 1.7 kpc or ε=0.016 for h_g=200 pc, the ring is located at ϖ=3.5 kpc.

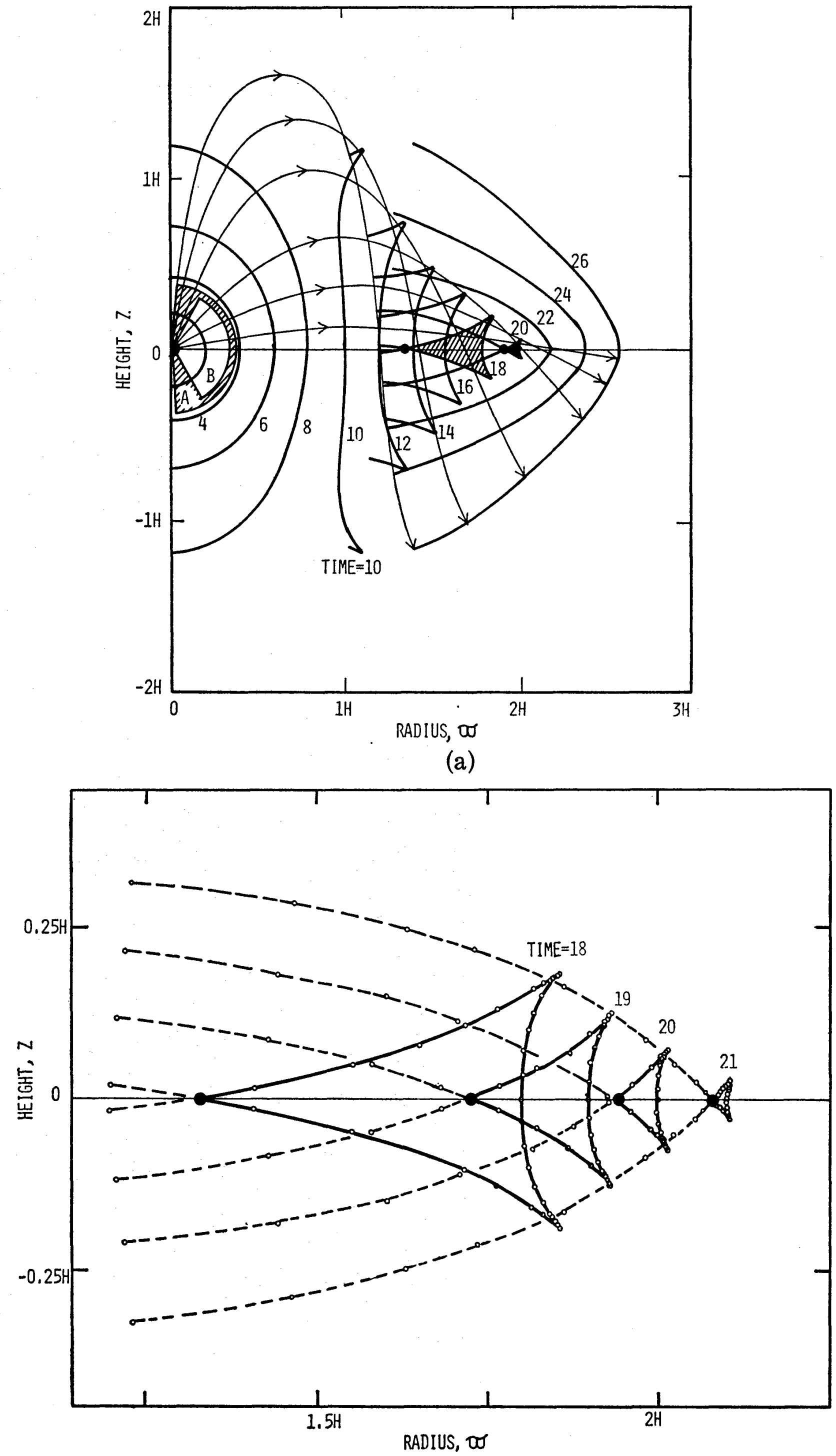

Fig. 1. (a) Propagation of ray-paths (thin lines) and wave fronts (thick lines) on the (ϖ, z)-plane for fast-mode MHD waves emitted isotropically from the galactic center. Indicated are times in units of $(H/2\,\mathrm{kpc})\times(V_0/20\,\mathrm{km\,s^{-1}})^{-1}\times 10^7\,\mathrm{yr}$. Cones A and B include, respectively, 99 and 90 percent of the front surface. If we take $H=1.7\,\mathrm{kpc}$, the "focal ring" (dark area) is located at $\varpi=3.5\,\mathrm{kpc}$. (b) The same as (a) but enlarged for wave fronts at $t=18$–21. Dashed lines indicate the fronts having crossed over the galactic plane. Small circles indicate positions of the wave packets.

Most of the wave front focuses on this ring, except for a small portion emitted with a large angle to the galactic plane which undergoes the "aberration." Cone A includes 99 percent of the MHD wave energy, which converges into a narrow ring with a triangular cross section as indicated by the hatched area in figure 1a. Aberration-free packets at projection angles less than 60° to the galactic plane (cone B), and therefore ~90 percent of the wave energy, converge into a small region with a dimension of $\sim 0.05H$ as indicated by the dark area in the figure, if no dissipation of the waves takes place.

The dissipation rate γ for small-amplitude MHD waves defined by the relation, amplitude$\propto\exp(-\gamma x)$, is given by (LANDAU and LIFSHITZ 1960)

$$\gamma=\frac{\omega^2}{2V^3}\left(\frac{\eta}{\rho}+\frac{c^2}{4\pi\sigma}\right), \tag{11}$$

where ω is the frequency of the waves, η the viscosity, σ the electric conductivity, c the light velocity, and x is the distance along a ray-path. In the circumstance under consideration, the second term is sufficiently small compared with the first. We take the density and temperature typically as $0.1\,\mathrm{cm}^{-3}$ and 100 K. The frequency ω is approximately $\omega\approx 2\pi V/l$, where l is taken to be equal to the width of the 3-kpc arm, or $l\approx 300$ pc. Assuming $V=20\,\mathrm{km\,s^{-1}}$, we have $1/\gamma\approx 10^4$ kpc if we adopt the molecular viscosity for η, and $1/\gamma\approx 10$ kpc if we adopt a turbulent viscosity due to the cloud-cloud collisions in the interstellar space. This implies that the dissipation is practically negligible.

Figure 2 shows the calculated result for the case that the source point of the

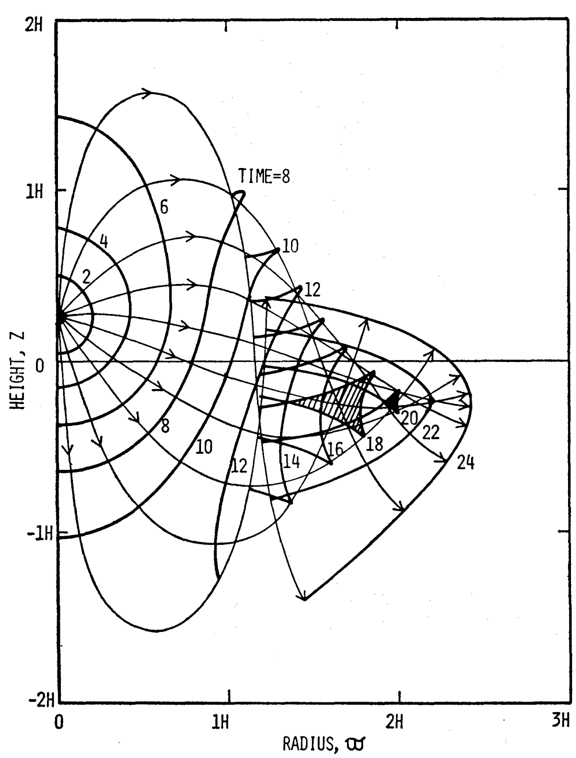

Fig. 2. The same as figure 1a but for the initial location of the wave source at $z_0=0.25H$ ($=0.4$ kpc) above the galactic plane. The focal ring appears at $z=-z_0=-0.4$ kpc.

waves is located at $z_0=0.25H$ ($=0.4$ kpc) above the galactic plane. Here we again take H as 1.7 kpc. The ray-paths are essentially the same as in the case of $z_0=0$, except that the convergence ring appears 400 pc below the galactic plane. The "image" is somewhat worse because of the "coma aberration" due to an "off-axis" focusing. More generally, the focusing of the front takes place at $\varpi\approx 2H$ and $z\approx -z_0$ independent of the source position, insofar as z_0 is not so large ($\lesssim 0.5H$). The aberration-free wave front focuses on a thin ring with a cross section of a scale of $\sim$80 pc at $t=1.6\times 10^8$ yr.

4. *Discussion*

We have so far shown that the fast-mode MHD waves emitted isotropically at the galactic center converge into the focal ring in the gaseous disk. If we take the scale height H of the Alfvén-velocity variation to be 1.7 kpc, the ring is located at 3.5 kpc from the galactic center. In view of the high efficiency of the convergence, we may expect that a substantial portion of the MHD-wave energy will be transformed to kinetic energy to drive the expanding motion of the gas in the 3.5-kpc ring.

The conservation of energy flux along a tube of ray-paths leads to a relation, $\mathscr{E}VS=$constant, where $\mathscr{E}$ and S are the energy density and the front area in the tube, respectively. As the wave front approaches the focal ring and re-enters the gaseous disk, the front area S decreases rapidly, and $\mathscr{E}$ increases correspondingly (figure 3). This rapid increase in $\mathscr{E}$ will yield a strong shock front with a higher velocity amplitude than V_0. At the shock front, the gas will be compressed as highly as several times that in the surrounding region. The compression would be radial, since the magnetic field lines are considered to be parallel to the galactic plane and concentric with the galactic center, being wound by the differential rotation of the disk. Such a shock compression is in agreement with observation that the gas density in the 3-kpc arm is a few times greater than that in the surrounding region.

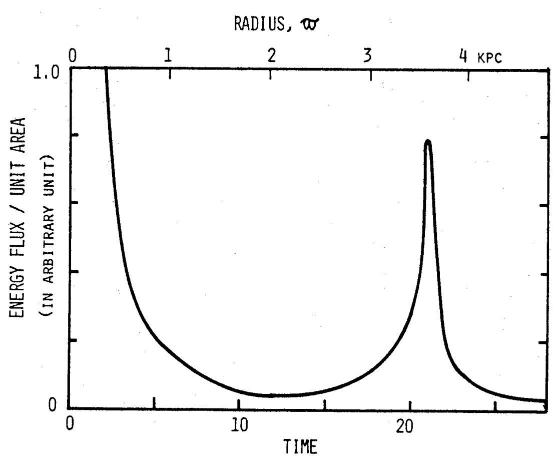

Fig. 3. Variation of relative energy flux through unit area at the front surface along a tube of ray-paths emitted within 50° to the galactic plane, for the same case as in figure 1. Indicated at the top of the figure is the radius of the front in the galactic plane when $H=1.7$ kpc.

Now we consider the wave propagation close to the galactic nucleus where the front is regarded as a spherical shock wave. We estimate at first a radius r_0 at which the spherical shock from the nucleus reduces to sub-Alfvénic. At $r>r_0$, we have, from the energy flux conservation, $(\rho v^2 V\cdot 4\pi r^2)_{\text{near gal.center}}=(\rho v^2 VS)_{\text{at 3-kpc arm}}$, where v is the wave amplitude. If we take that $\rho=0.5\,\text{cm}^{-3}$, $v=50\,\text{km s}^{-1}$, and $V=20\,\text{km s}^{-1}$ at the 3-kpc arm, and tentatively $\rho\cong 0.2\,\text{cm}^{-3}$ and $v=V\cong 100\,\text{km s}^{-1}$ at $r=r_0$, then we obtain a relation $4\pi r_0{}^2\cong 0.25S$. The front surface at the focal ring can be estimated from the computed front configuration in figure 1, and consequently we have $r_0 \cong 300$ pc. Here we have taken V as large as the observed equivalent turbulent velocity at $\varpi \approx 300$ pc. Since the wave propagation at $\varpi \lesssim 500$ pc is almost spherical, the adoption of a different value for V in the nuclear region does not significantly affect the situation of propagation outside there.

When $r < r_0$, the wave motion could be represented by a strong spherical shock wave. If we apply SEDOV's (1959) similarity solution for spherical explosion in gas, the energy E liberated during the point explosion at the nucleus is related to r and the propagation velocity of shock c_s through $E = (5/2)^2 \rho c_s^2 r^3$. Substituting $\rho \cong 0.2\,\mathrm{cm}^{-3}$, $c_s \cong V \cong 100\,\mathrm{km\,s^{-1}}$, and $r = r_0 \cong 300$ pc, we obtain $E \cong 2 \times 10^{53}$ erg, only by a factor of two greater than the observed kinetic energy of the 3-kpc arm. In the above estimate, we have assumed that all of the shock-wave energy is given to the fast-mode MHD blast wave at $r > r_0$. In reality, a variety of modes of waves would be excited, somewhat decreasing the conversion efficiency. However, in any case, far less explosive energy is needed to drive the 3-kpc arm, compared with the huge amount of kinetic energy, $\sim 10^{58-59}$ erg, as required in the model of SANDERS and PRENDERGAST (1974).

Leaving aside the energetics, the angular momentum problem, that the 3-kpc arm is rotating with an angular velocity approximately equal to the local galactic rotation at 3.5 kpc, or $v_\theta = 210\,\mathrm{km\,s^{-1}}$, would be naturally solved, because the energy transmission is made by the MHD waves propagating through the halo, not necessarily associated with a large-scale flow of matter. It is also noticed that the disk matter does not undergo a violent disturbance in spite of the efficient energy transfer.

Observation shows that the 3-kpc arm is not exactly on the galactic plane, but slightly away from it (ROUGOOR 1964). This z-asymmetry could be accounted for if the location of the wave source is away from the galactic plane. Indeed, the location of the source point z_0 has been shown to be directly associated with the location of the converging ring which appears at $z = -z_0$. Alternatively, the z-asymmetry might represent an asymmetry of H above and below the plane or a large-scale irregularity of the gas and magnetic fields. An asymmetry of H by only two percent produces the displacement of the arm by 30 pc from the galactic plane.

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