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Magnetohydrodynamic Disturbances from Galactic Nuclei. Formation of Double Radio Sources and Huge Galactic Bubbles

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Abstract

Propagation of fast-mode magnetohydrodynamic (MHD) waves from a galactic nucleus through a magnetized disk and halo is computed for various distributions of the Alfvén velocity. If the Alfvén velocity, V, is lower in the disk than in the halo as in spiral galaxies (low-V disk model), the waves form bisymmetric huge bubble-like fronts in the halo. The anomalous radio arms in NGC 4258 are interpreted by this model. On the other hand, if the Alfvén velocity in the disk is much higher (high-V disk model), the waves are collimated into two oppositely directed beams perpendicular to the disk. A continuous activity in the high-V nuclear disk will supply sharp twin beams of MHD disturbances, which will be responsible for double radio sources.

Key words: Double radio sources; Galactic activity; Galactic halo; MHD waves.

1. *Introduction*

Activities in nuclei of galaxies are believed to cause bisymmetric nonthermal radio features like double radio sources, head-tail galaxies, and anomalous radio arms in NGC 4258. Current models for the formation of directed jets may be classified into (a) the single explosion model (Sakashita 1971; Sanders 1976; Möllenhoff 1976; Wiita 1978; Morita and Sakashita 1978) and (b) the twin continuous beam model (Rees 1971; Blandford and Rees 1974; Scheuer 1974). In the single explosion models the collimation of released energy is rather broad: Sanders' (1976) calculation shows that the released energy is collimated into a beam 25° wide, which may explain double sources with relatively broad components. On the other hand, the continuous beam model seems promising to explain such compact components as those in Cyg A (Hargreve and Ryle 1974), although the origin of the beam has not been discussed in a fully quantitative way, and we have to search for an efficient mechanism of collimation.

In the current beaming theories the effect of magnetic fields in the nuclear regions of galaxies has not been fully taken into account. In the present paper we study the propagation of magnetohydrodynamic (MHD) disturbances from the nucleus of a galaxy, taking into account the effect of magnetic fields in the form of Alfvén velocity distributions.

2. *Propagation of MHD Waves in Galaxies*

The method to trace fast-mode MHD waves in a magnetized plasma (Uchida 1970) has been applied to galactic-scale phenomena associated with the galactic center activity, and to supernova remnants interacting with interstellar clouds [Sofue (1976, 1977, 1978); these are referred to as Papers I, II, and III]. If the distribution of the Alfvén velocity V is given and the condition that $V^2 \gg c_s^2$ is satisfied, we can trace the three-dimensional propagation of the MHD wave packets in the galaxy. Here c_s is the sound velocity. We treat here the fast-mode MHD waves in the WKB approximation, assuming that the wave amplitudes are small.

The condition $V^2 \gg c_s^2$ has been shown to hold in the central region of our Galaxy (Paper I). In the normal intercloud space of our Galaxy, where the gas density is $n \approx 5\times10^{-2}\,\mathrm{cm}^{-3}$ and the mean magnetic field strength $B \approx 4\times10^{-6}\,\mathrm{G}$, we have $V \approx 40\,\mathrm{km\,s}^{-1}$ and the sound velocity $c_s \approx 10\,\mathrm{km\,s}^{-1}$, yielding $V^2 \gg c_s^2$. In interstellar H I clouds, we have $B \approx 10^{-5}\,\mathrm{G}$ and $n \approx 10$–$100\,\mathrm{cm}^{-3}$ with $c_s \approx 1\,\mathrm{km\,s}^{-1}$ ($T \approx 100\,\mathrm{K}$), which leads again to $V^2 \gg c_s^2$. On theoretical grounds, the opposite might be expected. It appears that the galactic magnetic field is built up by a dynamo mechanism and the gas pressure is larger than or balanced with the magnetic pressure, i.e., $V \sim c_s$. However, even in such a circumstance the condition $V^2 \gg c_s^2$ may hold outside the galactic gaseous disk, namely, in the halo more than 200 pc above the galactic plane, because the z-scale height of the magnetic field is expected to be much larger than that of the gas. We assume here that the condition $V^2 \gg c_s^2$ holds in the whole Galaxy including the halo. In contrast, we have far less knowledge about gaseous and magnetic conditions in elliptical galaxies. However, it is likely that an elliptical galaxy in active phase has a compact nuclear disk where the magnetic fields are frozen in the gas and tightly wound by strong differential rotation so that the magnetic pressure exceeds the thermal pressure of the disk gas. In the following, we extend the condition $V^2 \gg c_s^2$ to nuclear disks of active elliptical galaxies as well as to spiral galaxies.

For the V distribution we assume the following form:

$$V = V_0\left[1+\Delta\exp\left(-\frac{x^2}{X^2}-\frac{y^2}{Y^2}-\frac{z^2}{Z^2}\right)\right], \tag{1}$$

where (x, y, z) are the Cartesian coordinates, (X, Y, Z) are constants giving the sizes of the magnetized disk, V_0 is Alfvén velocity far away from the galactic center, and Δ is a constant to specify either an enhancement in V ($\Delta>0$) or a depression ($\Delta<0$) at the galactic center. A limiting case of $X=Y=$infinity expresses a plane-parallel distribution of V which varies with height z alone from the galactic plane. As shown in Papers I and II, we may assume that $\Delta<0$ in our galactic disk. This means that the Alfvén velocity increases steeply with z and tends to a constant value V_0 in the high-z region. This type of V distribution may be common for normal spiral galaxies which have gaseous disks. On the other hand, the distributions of gas and magnetic fields in elliptical galaxies are not clear, and we examine below both possibilities of $\Delta<0$ and $\Delta>0$. The former presumes a V distribution similar to that in spiral galaxies and the latter a nuclear disk with strong magnetic fields.

3. *Results*

Following Paper II, we trace the ray paths of the MHD wave packets radiated isotropically from nuclei of galaxies, and examine the propagation of their wave fronts. We demonstrate typical results of the calculations.

(i) *Huge Galactic Bubbles (HGB) and a Focal Ring: Low-V Disk Model*

We consider first a case that the V-distribution is plane-parallel and V increases with height z from the galactic plane, tending to a constant value V_0 at high z. We take a parameter combination: $\Delta=-0.9$, $X=Y=$infinity, and $Z=1$ unit length. The propagation of the MHD wave front and the ray paths are shown in figure 1. Approximately 80% of the isotropically radiated wave packets are reflected in the galactic halo due to the steep increase in V toward high z, and converge into a ring at $\varpi=(x^2+y^2)^{1/2}\approx 2Z$. The remaining part of the front expands into the halo, forming there bisymmetric huge galactic bubbles (HGB). (See Paper II for detailed discussions.)

(ii) *Collimation of the MHD Waves and Beaming*

(a) *High-V disk model.* We consider next a case that V decreases rapidly with increasing z (a high-V disk model). The parameter combination taken is: $\Delta=20$, $X=Y=$infinity, $Z=100$ pc. We presume a nuclear disk where the magnetic field strength is so high that the Alfvén velocity at the galactic center is about 20 times the velocity in the halo region. Figure 2 shows the propagation of the wave front and ray paths. The rays are strongly refracted by the disk and bent almost perpendicular to the disk plane. When they come out of the disk, the waves are highly collimated into a beam of half-width of about 20° as shown by the inserted "beam pattern," namely, the angular distribution of the relative wave amplitude which is inversely proportional to the surface area of

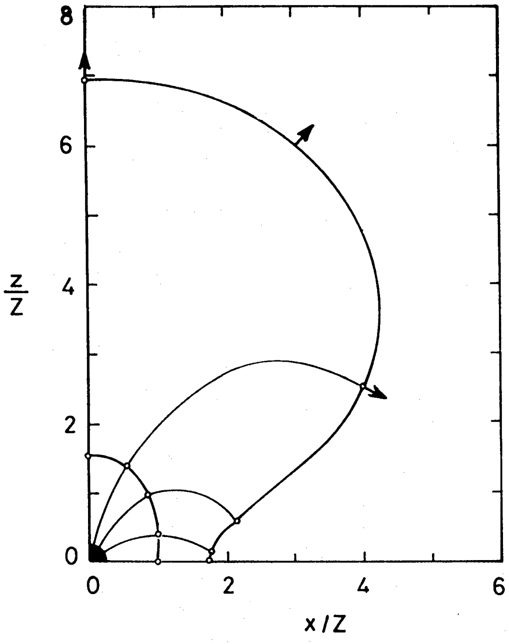

Fig. 1. MHD wave front (thick lines) and ray paths (thin lines) from a galactic center. The galactic disk has a lower Alfvén velocity (low-V disk) than in the halo as expressed by equation (1). Parameters are $\Delta=-0.9$, $Z=1$, $X=Y=\infty$. Coordinate scales are in units of Z.

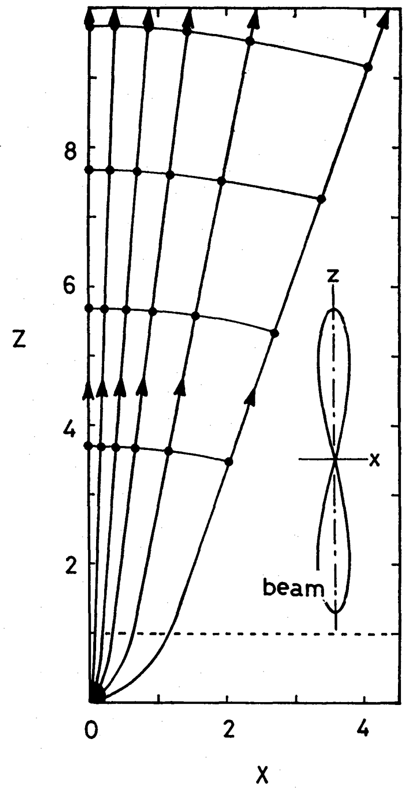

Fig. 2. MHD wave front and ray paths from a galactic center with a higher Alfvén velocity in the disk (high-V disk) than in the halo. Parameters are $\Delta=20$, $Z=100\,\mathrm{pc}$. The coordinate scales are in units of $Z=100\,\mathrm{pc}$. The inserted "beam pattern" shows the distribution of the relative wave amplitude at infinity.

the front.

In addition to the plane-parallel disk we may suppose that there exists a high-density central core which is condensed due to the gravitational attraction of a massive point mass at the center as is discussed by Sanders (1977). If we introduce here such a central core of high gaseous density, the Alfvén velocity in and around the core will be reduced. We express the Alfvén velocity in the form:

$$V=V_0\left[1+\Delta_1\exp\left(-\frac{z^2}{Z^2}\right)+\Delta_2\exp\left(-\frac{r^2}{R^2}\right)\right], \tag{2}$$

with $\Delta_1>0$ and $\Delta_2<0$, where $r=(x^2+y^2+z^2)^{1/2}$. The second term represents the high-V nuclear disk of scale height Z and the third corresponds to the central high-density, low-V core of radius R. Figure 3 shows the calculated ray paths and wave fronts for $\Delta_1=20$, $\Delta_2=-10$, and $Z=R=100\,\mathrm{pc}$. The Alfvén velocity distributions are indicated with the dotted lines in the figure. We find a sharp collimation of the waves along the z-axis as illustrated by the inserted beam pattern. The half-power width is approximately 4°. We note that a considerable fraction of the isotropically radiated wave front converges onto a focal point on the z-axis. It has been proved that the sharp collimation takes place for any value of Δ_2 smaller than -10.

(b) *High-V magnetic ring.* We consider further a rather sophisticated case which leads also to a high-efficiency collimation. A rotating ring with high

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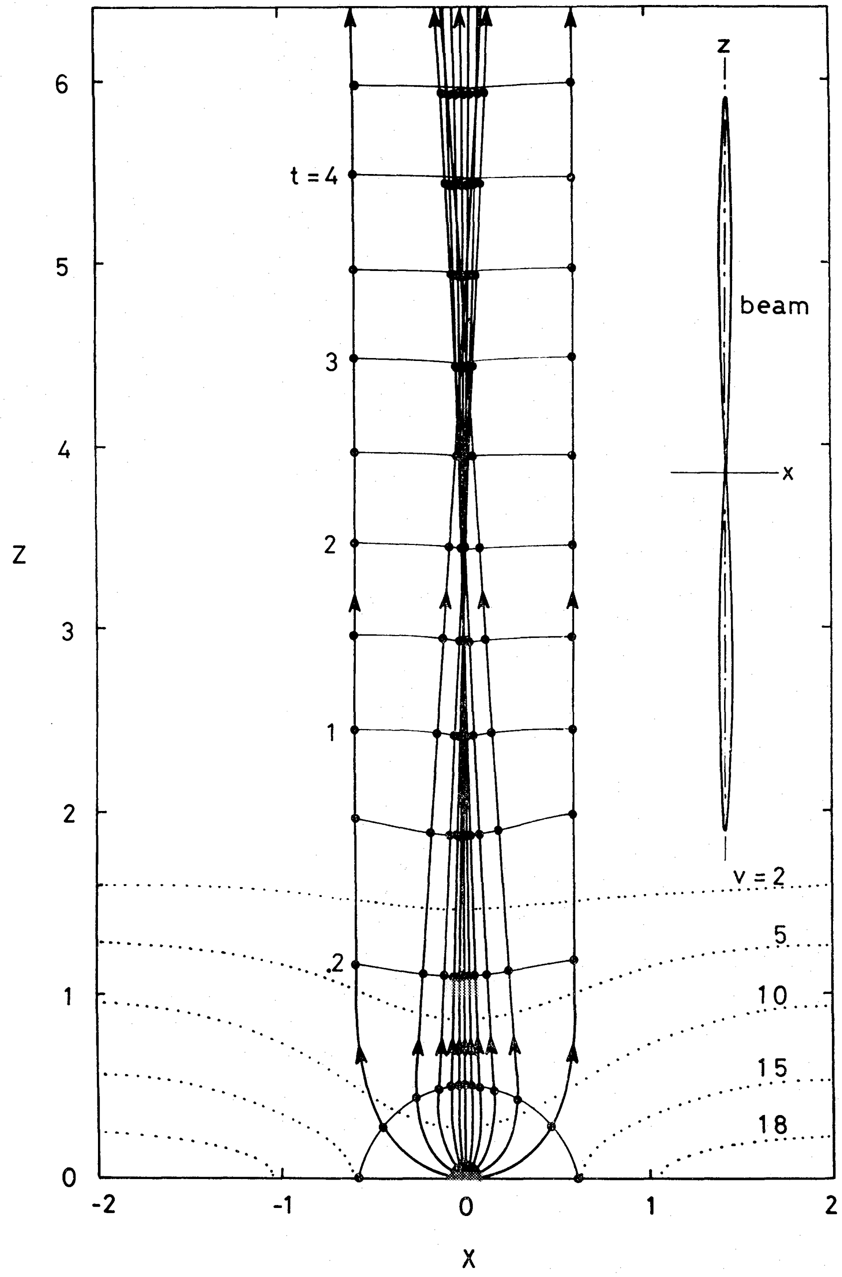

Fig. 3. The same as figure 2 but for the coexistence of a dense gaseous core of radius 200 pc. Parameters are $\Delta_1=20$, $\Delta_2=-10$, $Z=100$ pc, and $R=100$ pc in equation (2). Iso-Alfvén velocity contours are shown by dotted lines, where $v=V/V_0$. The coordinate scales are in units of 100 pc, and the time t in units of 100 pc V_0^{-1}.

Alfvén velocity around the galactic center may possibly develop through a gravitational contration of a rotating gaseous disk with frozen-in magnetic fields. We assume that the ring is located at $\varpi=\varpi_0=400$ pc and has a circular cross section of radius $a=200$ pc. The V distribution is given by

$$V=V_0[1+\Delta\exp\{-[(\varpi-\varpi_0)^2+z^2]/a^2\}]\ , \qquad (3)$$

where $\varpi=(x^2+y^2)^{1/2}$, and we take $\Delta=10$. The calculation shows similar ray paths and fronts to figure 3. The waves are strongly reflected by the ring and a con-

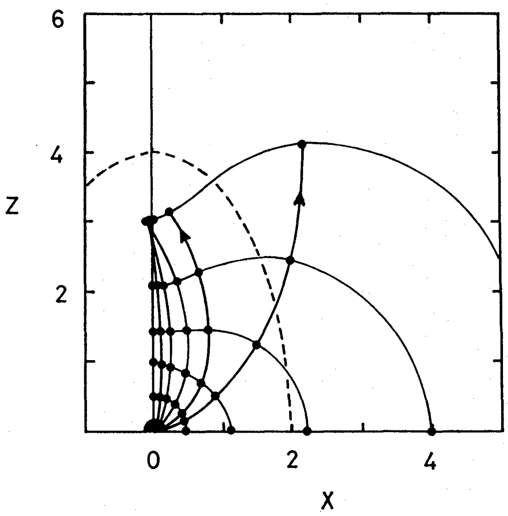

Fig. 4. The same as figure 1 but for an elongated nuclear spheroid expressed by equation (1) with the parameters $\Delta=-0.8$, $X=Y=200$ pc, $Z=400$ pc.

siderable part of the front focuses onto a point on the z-axis at $z=1$ kpc.

(c) *Low-V spheroid.* The next case is a spheriod of low Alfvén velocity. As a parameter combination, we take $\Delta=-0.8$, $X=Y=200$ pc, and $Z=400$ pc with the V distribution expressed by equation (1). The ray paths and wave front are shown in figure 4. Because of the lower Alfvén velocity inside the spheroid the rays are refracted, bent toward the z-axis, and focus onto a point at $z=300$ pc. The beam pattern is similar to that of figure 3 and a high-efficiency collimation is obtained. We note that the major axis of the spheroid does not necessarily lie along the rotation axis of the galaxy, but could lie within the galactic plane, for which we presume a rotating Maclaurin spheriod. In such a case the beam is perpendicular to the rotation axis, and the beam direction is not constant but rotates with the spheroid.

4. *Application*

We discuss some galaxies with peculiar radio features which may be explained by the present HGB model, and discuss a possible formation of double radio sources by the beaming of the MHD waves.

(i) *The HGB Model*

(a) *The North Polar Spur (NPS).* The prominent ridge in the background radio continuum in our Galaxy, the NPS, has been interpreted in many ways. Among them Papers I and II concern the galactic-scale explosion model for the spur: MHD disturbances produced by an explosion at the galactic center propagate through the galactic disk and halo. A considerable portion of the waves converges into a ring in the galactic disk away from the center by about $2.1Z$, where Z is the z-scale height of the V distribution. If $Z=1.7$ kpc and $\Delta=-0.7$ [equation (1)] the ring appears at $\varpi=3.5$ kpc, which will be responsible for the expanding "3-kpc arm." The remaining part of the front expands into the halo forming there an HGB, which will be observed as the NPS. Indeed the projection of the HGB on the sky at the epoch of formation of the 3-kpc arm fits reasonably well the observed radio ridge of the NPS (see Paper II for a detailed discussion).

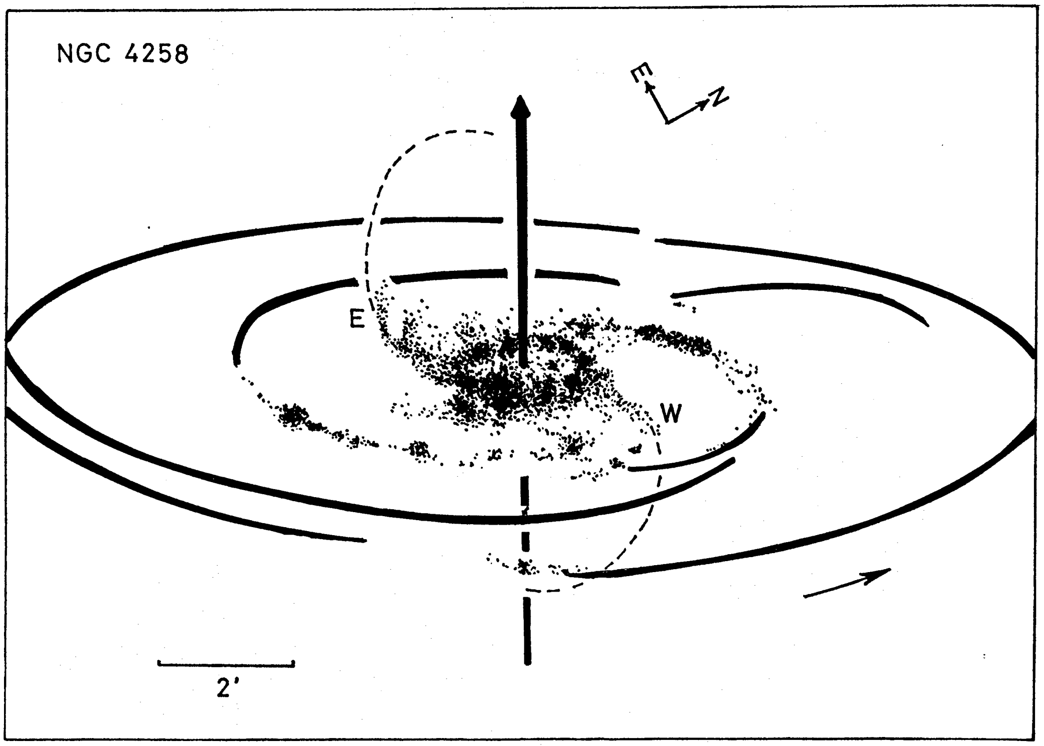

Fig. 5. A sketch of the normal optical arms [thick lines: Sandage (1961)], anomalous Hα arms [dots: Deharveng and Pellet (1970)], and the radio ridges of the anomalous arms [dashed lines; van der Kruit et al. (1972)] of the spiral galaxy NGC 4258.

(b) *NGC 4258.* This galaxy is known with its bisymmetric anomalous radio arms spirally emerging from its central region (van der Kruit et al. 1972; Oort 1977; van Albada 1978). They consider that the anomalous arms lie in the equatorial plane of the galaxy. However, the observational data so far published seem not enough to prove that they are in the equatorial plane. The following facts rather suggest that the arms are off the equatorial plane.

The radio brightness of the western anomalous arm (W in figure 5) is higher than that of the eastern arm (E) by a factor of 2–3 in the 21-cm continuum (van der Kruit et al. 1972). If this asymmetry is due to a difference in shock strengths in the two arms, we may expect a stronger Hα emission from the western arm rather than from the eastern arm. However a creful inspection of an Hα photograph of the galaxy (Deharveng and Pellet 1970) indicates clearly that the W arm is fainter than the E arm. We emphasize that the western Hα arm stops at a crossing point with a normal spiral arm where a strong dark lane is associated (figure 5). The two arms extend all the way to the edge of the galaxy, cutting through all the spiral arms. In particular the E-arm extends even beyond the outermost spiral arm. We recall here that the galaxy is "quiet" in the H I-line emission (van Albada 1978), which shows an undisturbed distribution of the H I gas in the disk and a normal rotation.

These facts are naturally understood, if the anomalous arms (W and E) are structures off the equatorial plane of the galaxy; the W arm is behind the galactic plane obscured by dusts in the disk, whereas the E arm is in front of it nearer to us. This configuration is consistent with the orientation of the rotation axis which runs from SW behind the page of figure 5 toward the NE nearer

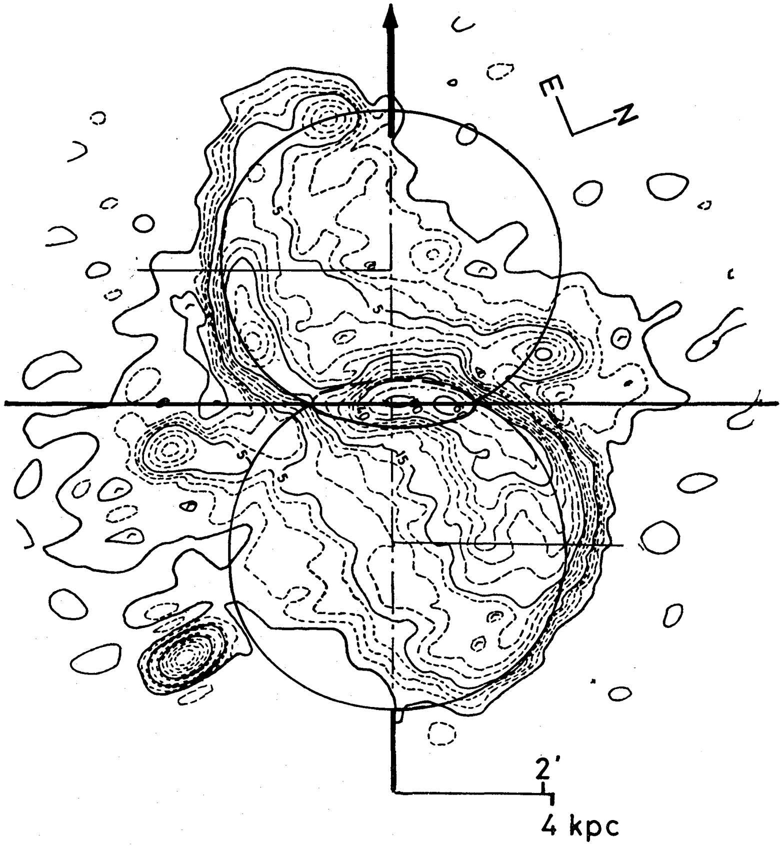

Fig. 6. The huge galactic bubbles (HGB) as the MHD wave front superposed on a radio contour map of NGC 4258 at 1420MHz from van Albada(1978). The two anomalous arms are well fitted with the calculated MHD front.

side to us. A possible interpretation of such a configuration is that the anomalous radio ridges are part of bisymmetric huge galactic bubbles in the halo of NGC 4258. In figure 6 we superpose the MHD front of figure 1 projected at an inclination angle of 20° on the radio contour map of van Albada (1978). Here the scale height Z is taken as 1 kpc. The front fits reasonably well the two anomalous arms.

(c) *NGC 3079*. The edge-on galaxy NGC 3079 has two radio spurs which emerge from the galactic disk in two opposite directions symmetrically with respect to its galactic center (de Bruyn 1977). These spurs may be understood also by the HGB model; they are part of the bubbles in the halo, but their top regions are too weak to be detected.

We note that the present MHD method is restricted to small-amplitude waves, which can reproduce only morphologically such peculiar radio features as the NPS and the anomalous arms in NGC 4258. For further quantitative discussions of magnetic field strengths and particle energies for their nonthermal radio emission, we need a nonlinear treatment of strong shock waves propagating into the galactic halo, which has been not yet subjected to a theoretical consideration and will be discussed in a separate paper.

(ii) *Double Radio Sources*

It is generally accepted that double radio sources like Cen A, 3C452, and Cyg A are produced by a highly collimated ejection of material from the galactic nuclei. One of the promising mechanisms of the directed ejection of beams is the twin exhaust model (Rees 1970; Blandford and Rees 1974; Scheuer 1974). We suggest here that the collimation of the MHD disturbances from a nuclear disk in section 3-ii will be a possible source for such a high-energy plasma beam; if a galaxy has a very high-V nuclear disk, a considerable fraction ($>90\%$) of the isotropically released energy in the form of MHD disturbances is collimated into sharp beams oppositely directed perpendicular to the galactic plane (figures 2 and 3).

In particular, as in figure 3, if there exists a dense gaseous core at the center of the nuclear disk, the collimation is so high that a focal point appears on the z-axis at z=500–1000 pc. Such a focusing will lead to a rapid increase of wave amplitudes resulting in strong shock waves. It is conjectured that the focusing shock develops into a strongly compressed region of magnetic fields, where high-energy particles are accelerated in the direction of the z-axis. If a galactic activity produces MHD disturbances continuously, the focusing beam will give rise to a continuous supply of high energy plasma beam.

5. *Summary*

Our results are summarized as follows: If a spiral galaxy has a gaseous disk where the Alfvén velocity is lower than that in its halo region, the MHD disturbances generated at a nucleus of the spiral galaxy suffer from a strong reflection in the halo. A considerable portion of the waves converge into a ring in the galactic plane, whereas the remaining part of the wave front makes bisymmetric huge galactic bubbles in the halo above and below the equatorial plane. The peculiar radio arms in NGC 4258, the radio spurs in the edge-on galaxy NGC 3079, and probably the North Polar Spur in our Galaxy may be due to such bubble-like fronts in their halos.

In contrast to spirals, elliptical galaxies are less abundant in the gaseous contents and have no large-scale galactic disk. However, it is likely that an elliptical galaxy has a compact nuclear disk. The magnetic fields frozen in the disk gas will be tightly wound so that the Alfvén velocity in the disk is much higher than in the surroundings. If this is the case, the MHD disturbances from its nucleus are strongly collimated towards the z-axis resulting in two sharp beams oppositely directed and perpendicular to the disk. The beams thus formed will be responsible for double radio sources often associated with elliptical galaxies.

We note that the present method can treat small-amplitude waves and predict the geometrical evolution of their fronts and ray paths. However, the method gives no knowledge about absolute quantities like wave amplitudes, magnetic field strengths, and energies of relativistic particles for the nonthermal radio emission. To obtain such quantities we need a non-linear MHD treatment of the problem, which is beyond the scope of the present paper. We note also that the observed asymmetry of the anomalous arms of NGC 4258 and the North Polar Spur with respect to their rotation axes remains still open to question.

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