On the Accretion Wake Model of Radio Jets of Galaxies

By

Shin YABUSHITA*

(Received September 29, 1978)

Abstract

The possibility is investigated as to whether jet streams associated with a galaxy or a quasar are explicable as accretion wakes which form when a gravitating body moves through an intergalactic medium with supersonic speed. A comparison of the theory based upon column accretion with a recently observed radio jet of NGC6251 gives good agreement regarding the geometrical shape of the jet and energy stored therein, provided the relative motion has a large Mach number and intergalactic density $\sim 2\times10^{-28}$/gcm^{-3} is assumed. Again, the observed nuclear jet of NGC 6251 may be explicable along these lines. An accretion hypothesis is specific enough to relate the density and magnetic field in the jet to those of intergalactic gas. Galactic radio jets observed so far are one sided. As for any model which ascribes jets to an outburst of relativistic particles emerging in two opposite directions from a galactic nucleus, it remains to explain the above observed result.

1. Introduction

Two recent radio observations by Wagget, Warner & Baldwin$^{1)}$ and Readhead, Cohen & Blandford$^{2)}$ of the elliptical galaxy NGC6251 have revealed remarkable jet streams associated with it. Firstly, the galaxy has a jet stream (which we will call a galactic jet to distinguish it from a nuclear jet, to be referred to later) 200kpc in length and 10kpc in width. Secondly, there is a much smaller jet emerging from the nuclear region of the galaxy which is 1.7pc in length and 0.1pc in width. These two jets appear to be aligned in the same direction. Among models which have been advanced for explaining extended radio sources, the bubble model of Gull & Northover$^{3)}$ and the twin exhaust model of Brandford & Rees$^{4)}$ should be mentioned. The former hypothesis is that a bubble of light plasma is formed at the nuclear region of a massive galaxy ($10^{13}M_\odot$) immersed in a very dense intracluster gas. By the rotation of the nucleus, the bubble is likely to divide into two which ascend by buoyancy. Presumably, two jet streams will be left behind the bubbles as they advance. The latter assumes that highly ener-

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* Department of Applied Mathematics and Physics

getic particles are formed in the nuclear region. Then by the rotation of the nucleus, the energetic fluid rises in two directions parallel to the rotational axis, which in turn is connected to exterior regions through two de Laval type nozzles. The flow is supersonic beyond the sonic point and is relativistic. A brief discussion of the models will be given in section 7.

In this paper, we wish to consider the possibility that the observed jet streams may be the result of interactions of a galaxy (or a quasar) and the galactic nucleus with interagalactic gas. As is well known, when a gravitating body moves through a gas cloud, an accretion wake forms behind the body owing to gravitational force. Hence, there is a possibility that the observed galactic jet may be such an accretion wake. The discussion is admittedly rather crude. However, it will be shown that quantitative agreement with the observation is obtainable for a reasonable model of the galaxy.

There are several radio sources with similar jet and nuclear radio structures, such as 3C147, 3C236 and 3C237. 3C236 is identified with an elliptical galaxy⁵⁾. Again, the well known optical jet of M87 has a similar structure⁶⁾. Therefore, we will consider the interaction of an elliptical galaxy (with mass $\sim 10^{12}M_\odot$) with intergalactic gas.

2. Observational requirements

The jet streams associated with galaxy NG6251 are the most remarkable and closely observed ones among systems which emit non-thermal radiations. Any hypothesis which aims at their explanation must be capable of explaining three important features of the jets. These are the geometrical shape of the jet, the energy which is stored therein and the nuclear jet. The radio observation by Wagget *et al.* shows that the galactic jet has *conical* cross section. Secondly, the minimum energy stored in the galactic jet of NGC6251 is estimated by Wagget *et al.* at 8×10^{57} erg.

In the accretion wake model of the galactic jet to be developed in the present paper, we will mainly concentrate upon the three main features mentioned above. The accretion process is characterized by a fairly small number of parameters. These are M, the mass of the galaxy, V_∞, the velocity of M relative to the ambient gas, ρ_∞, the density of the gas, and c_∞, the velocity of sound. The choice of M is limited because the observational data so far indicate $M\sim 10^{12}M_\odot$, although there is no definite and reliable estimate of mass for quasars. The temperature and density of intergalactic gas is not well known, but the temperature (T) is in the neighbourhood of 10^6K, so that $c_\infty \sim 10^5\,\mathrm{kms}^{-1}$. The density ρ_∞ is particularly difficult to estimate but Oort⁷⁾ estimates that the local group of galaxies probably contains gas of a density $\sim 3\times 10^{-28}\mathrm{gcm}^{-3}$. This value is consistent with the observed rate of infall of matter into our galaxy[8]. Again, since the peculiar velocity of galaxies which are not cluster members is of the order of 100 kms^{-1}, V_∞ ought to be at most several times this value. Thus, the choice of parameters is fairly limited, which sigifies that the accretion wake model can be tested with observation without much ambiguity, unlike other models..

3. Geometry of accretion column

In two recent papers by Yabushita[9-10], the theory of column accretion has been developed by taking into account the pressure effect which had been neglected in the original discussion of the accretion process by Bondi & Hoyle[11] The basic assumption is that the Mach number, $\boldsymbol{M}_\infty$ $(=\mathrm{V}_\infty/\mathrm{c}_\infty)$ is much greater than unity, so that gas particles before reaching the accretion column may be regarded as collision free. The physical state of the column is characterized by p (pressure), ρ (density), u (velocity away from M), and s (radius of the column). By considering the balance of momentum, Bondi & Hoyle derived the relation that

$$p=\frac{A}{2\pi s}\left(\frac{2GM}{r}\right)^{1/2} \tag{3.1}$$

where

$$A=\frac{2\pi GM\rho_\infty}{V_\infty} \tag{3.2}$$

is the amount of material which falls on the unit length of the column per unit time, and where r is the distance from M. Hence, if pressure p is given, the radius s is at once obtainable.

In order to calculate p, an investigation somewhat closer than the one given in[10] is needed. The Bernoulli equation which describes the conservation of energy reads (cf. reference 12).)

$$\frac{1}{2}u^2+\frac{\gamma}{\gamma-1}\frac{p_\infty}{\rho_\infty}\left(\frac{\rho}{\rho_\infty}\right)^{\gamma-1}-\frac{GM}{r}=\frac{1}{2}V_\infty^2+\frac{\gamma}{\gamma-1}\frac{p_\infty}{\rho_\infty},$$

where we have assumed that the gas is adiabatic;

$$\frac{p}{p_\infty}=\left(\frac{\rho}{\rho_\infty}\right)^{\gamma}.$$

However, we have the relation that $c_\infty^2=\gamma p_\infty/\rho_\infty$, so that the above equation may be expressed in the form

$$\frac{1}{2}u^2+\frac{1}{\gamma-1}c_\infty^2\left(\frac{p}{p_\infty}\right)^{(\gamma-1)/\gamma}-\frac{GM}{r}=\frac{1}{2}V_\infty^2\left(1+\frac{2}{\gamma-1}\boldsymbol{M}_\infty^{-2}\right).$$

The second term on the right hand side may be neglected, because $\boldsymbol{M}_\infty \gg 1$. Pressure p is therefore given by

$$p = p_\infty \left\{ \left(\frac{1}{2} V_\infty^2 - \frac{1}{2} u^2 + \frac{GM}{r} \right) \cdot \frac{\gamma - 1}{c_\infty^2} \right\}^{\gamma/(\gamma-1)} \tag{3.3}$$

Introducing the non-dimensional variables x and y by the relations

$$r = \frac{GM}{V_\infty^2} x, \quad u = V_\infty y, \tag{3.4}$$

the above relation can be written in the form

$$p = p_\infty \left\{ \frac{1}{2} (\gamma - 1) \boldsymbol{M}_\infty^2 \left(1 - y^2 + \frac{2}{x} \right) \right\}^{\gamma/(\gamma-1)}. \tag{3.5}$$

The corresponding relation for density ρ is

$$\rho = \rho_\infty \left\{ \frac{1}{2} (\gamma - 1) \boldsymbol{M}_\infty^2 \left(1 - y^2 + \frac{2}{x} \right) \right\}^{1/(\gamma-1)}. \tag{3.6}$$

The differential equation satisfied by y has been derived earlier[10)].

$$A(x, y) \frac{dy}{dx} = B(x, y), \quad A(x, y) \equiv y^2 - \frac{\gamma - 1}{2\gamma} y^2 - \frac{\gamma - 1}{2\gamma} \left(1 + \frac{2}{x} \right)$$

$$B(x, y) \equiv -\frac{y}{x^2} + \frac{y^2(1-y)}{x - \alpha} + \frac{\gamma - 1}{2\gamma} \left[\frac{y^3}{x - \alpha} - \frac{y}{x - \alpha} \left(1 + \frac{2}{x} \right) + \frac{2y}{x^2} \right]$$

where $x = \alpha$ corresponds to a stagnation point. The radius s, of the accretion column, is therefore given by

$$s = \frac{GM\gamma\sqrt{2}}{c_\infty^2} \left\{ \frac{1}{2} (\gamma - 1) \boldsymbol{M}_\infty^2 \left(1 - y^2 + \frac{2}{x} \right) \right\}^{-\gamma/(\gamma-1)} x^{-1/2}.$$

To advance the theory further, it is necessary to specify a numerical value of γ. We assume that the intergalactic gas remains completely ionized, so that $\gamma = 5/3$. The above equation may be written in the form

$$s = \frac{5}{3} \cdot 2^{1/2} \cdot 3^{2.5} \boldsymbol{M}_\infty^{-3} \frac{GM}{V_\infty^2} k(x) \tag{3.7}$$

where we have defined that

$$k(x) \equiv \left(1 - y^2 + \frac{2}{x} \right)^{-2.5} x^{-1/2}.$$

We are interested in the ratio s/r;

$$\frac{s}{r} = \frac{5}{3} \cdot 2^{1/2} \cdot 3^{2.5} \boldsymbol{M}_\infty^{-3} \frac{k(x)}{x}. \qquad (\ 8$$

Since the observed jet of NGC6251 has a nearly conical section, the ratio s/r should remain nearly constant for the jet to be consistent with the accretion wake model. In Fig 1, we plot the functions $k(x)$ and $k(x)/x$. One one easily notices a nearly linear increase of $k(x)$ for a wide range of x. The last result is consistent with the accretion wake model.

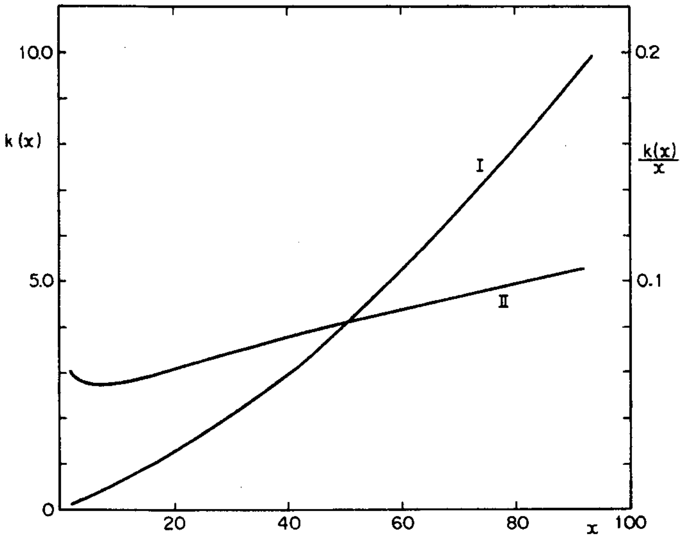

Fig. 1. The function $k(x)$ and $k(x)/x$ are plotted against x. x is proportional to the distance from the galaxy. The function $k(x)$ is proportional to the radius of the accretion column. $\alpha=2$ and $\gamma=5/3$. Note that $k(x)$ is nearly a linear function of x. $k(x)$ is denoted by I and $k(x)/x$ by II.

4. Relative velocity

Having calculated the radius of the accretion column, we now proceed to investigating whether it can be reconciled with the expected velocity of NGC6251. The projected length of the jet is 200kpc. Since it is unlikely that its direction is perpendicular to the line of sight, we tentatively adopt 300kpc as its total length. The diameter near the outer end is some 12kpc so that equation (3.8) gives that

$$\frac{5}{3}2^{1/2}\cdot 3^{2.5}M_\infty^{-3}\frac{k(x)}{x}\bigg|_{x=x_c} = 0.02\,,$$

where x_c corresponds to the outer end of the jet. As has been shown in section 3, the function $k(x)$ is approximately a linear function of x (distance from M). Its derivative $k'(x)$ remains fairly constant at 0.1. Therefore, the above equation gives the Mach number by

$$2^{1/2} \times 5 \times 3^{1.5} \boldsymbol{M}_\infty^{-3} = 0.2\,,$$

whence follows the result that $\boldsymbol{M}_\infty \fallingdotseq 5.6$. If an inter-galactic medium is assumed to be the completely ionized form of hydrogen, the velocity of sound c_∞ is 160 kms^{-1}, if the temperature is $10^6 K$. The relative velocity V_∞ then turns out to be 950 kms^{-1}. This is consistent with the remark of section 2.

5. Energy generation by the accretion process

In the idealized form of cold accretion where the Mach number is infinitely large, the impinging particle, when arriving at the accretion column, has a velocity V_∞ parallel to it, and a transverse velocity $(2GM/r)^{1/2}$. The transverse component of the velocity is brought to zero by collison with the gas particles within the column. There is a discontinuity of density and pressure at the column surface, which is a shock wave. The transverse component of the momentum is therefore used to heat up the column. In a steady state, the energy generation is given by AGM/r per unit length per unit time. Hence, the total energy generated within the column is given by

$$I = AGM \int_{r_0}^{r_c} \frac{1}{r} dr = AGM \log \frac{r_c}{r_0}\,, \tag{5.1}$$

where r_0 and r_c are the lower and upper limits of integration, respectively. For the system NGC6251, r_c should be $\sim$300 kpc. There is some ambiguity regarding how to choose an appropriate value of r_0. We tentatively assume that r_0 is comparable with the distance of the stagnation point $(= \alpha GMV_\infty^{-2})$, where α is a number of order unity.

To evaluate the numerical value of I, the mass M has to be assumed. Since NGC6251 is an elliptical galaxy, we tentatively adopt $M = 10^{12} M_\odot$, which is generally true for such galaxies[13)]. Adopting $V_\infty \sim 900\ \mathrm{kms}^{-1}$, arrived at in the pevious section, the distance of the stagnation point turns out to be some 5.3 kpc. The numerical factor is $\log r_c/r_0 \sim 4$. Adopting $2 \times 10^{-28}\ \mathrm{gcm}^{-3}$ as the unperturbed density, $AGM \sim 2.5 \times 10^{41}\ \mathrm{ergs}^{-1}$, so that $I \sim 10^{42}\ \mathrm{ergs}^{-1}$. Now, to travel the observed length of the galactic jet (assumed to be 300 kpc) with a speed of $10^3\ \mathrm{kms}^{-1}$ requires at least 3×10^8yr. Thus, the energy generated within this interval of time turns out to be 9×10^{57} erg. Although this value is already close to the minimum estimate of the energy (8×10^{57} erg) stored in the NGC6251 jet, yet when the efficiency of the radio wave emission is taken into account, the energy generation may appear to be deficient. In this respect, one should remember that the energy generation is proportional to M^2.

The mass of $M87$, which is accompained with an optical jet is estimated at $3\times10^{31}M_{\odot}$ by Arp & Bertola[14]*. Arp *et al* argue that elliptical galaxies may have masses of an order of magnitude greater than the currently accepted value ($10^{12}M_{\odot}$). Again, the gas density[15] in the local group may be as high as 8×10^{-28} gcm^{-3}, corresponding to 5×10^{-4} particles cm^{-3}. Thus, by increasing the adopted values of M and ρ_{∞} by amounts which are not inconsistent with the observation, the energy stored in a galactc jet can be accounted for.

The quasar 3c237 is associated with a jet. The jet luminosity in the optical region is estimated at 2×10^{43} ergs^{-1}[22]. Assuming that the jet is in a steady state, the luminosity can be accounted for by a quasar having $M\sim4\times10^{12}M_{\odot}$ moving through intergalactic gas with $\rho_{\infty}\sim2\times10^{-28}$ gcm^{-3}. Finally, we wish to point out that the temperature relaxation time of ionized hydrogen is given by $t_T\simeq10^4\,TN^{-1}(1+4.7\times10^5T)^{-1}yr$, where T is the temperature and N is the number of electrons per cubic centimeters[16]. For the $M87$ jet, $N\sim10^{-2}$ cm^{-3}[6]. Putting $T\sim10^6K$, t_T turns out to be some 7×10^8yr. A higher temperature gives a longer relaxation time. Hence the jet may be regarded as remaining nearly adiabatic during 3×10^8yr, which is needed for the formation of the remarkable jet of *NGC* 6251.

6. Nuclear jet

The observation of NGC6251 by Readhead *et al*[2] has shown the existence of a jet which emerges from the nuclear part of the galaxy. Its length is 1.7pc and width 0.1pc. It remains to investigate whether or not the nuclear jet can be explained by the hypothesis that the galaxy is moving through dense intergalactic gas with supersonic velocity.

Lyttleton & Bondi[17] discussed gas accretion by a galaxy which has a finite radius. Gas enters the galaxy both from the front and rear sides. They assumed that the gas accreted by the galaxy is used for spiral structure formation, and did not consider the induced gas flow therein. It is true that the accreted gas will be turned into stars eventually. The flow pattern which might be set up within a gravitating sphere with a finite rate of gas consumption (into star formation) is a difficult problem not yet tackled. However, a simple consideration leads to a result that there will be a net flow in the general direction of the unperturbed flow. The ratio of gaseous material entering from the front side to the one from rear side is given by[17]

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* A modest estimate of M 87 mass is obtainable if mass to light ratio of 50 is assumed. The mass turns out to be $1.2\times10^{13}M_{\odot}$[15].

$$\frac{1-\Theta^2-\Theta^4}{\Theta^2+\Theta^4}, \quad \Theta = V_\infty\left(\frac{2GM}{R_g}\right)^{-1/2}$$

where R_g is the radius of the galaxy. If $\Theta > 0.7861$, the gas enters the galaxy only directly (front side). If we adopt numerical values $V_\infty = 10^3 \mathrm{kms}^{-1}$, $M = 10^{12} M_\odot$ and $R = 10\mathrm{kpc}$, the numerical value of Θ turns out to be some 2.5. Thus a flow will be set up in the galaxy in the direction of the unperturbed velocity. It is therefore likely that a galactic nucleus is immersed in a gaseous stream.

We now turn to investigating a possible consequence of a strong outflow of gas from the nuclear region. (For reviews of galactic nuclei, see references 18) and 19)). The situation is somewhat like the the interaction of a comet with the solar wind. The solar wind is an ionized plasma which consists mainly of protons and electrons and flows away from the sun. The velocity is supresonic Since the temperature is 10^5K, the Mach number of the flow is approximately 10. Again, the orbital velocity of a comet is $\sim 10^2 \mathrm{kms}^{-1}$, so that the relative velocity is $M_\infty \sim 10$. The gas which evaporates from the surface of a cometary nucleus is blown away by the solar wind which is recognized as a Type I tail (See Fig. 1 in 20)). Isophotes of a comet (Fig. 1 in reference 21)) shows the presence of a narrow plasma tail emerging from the nucleus. If one compares the equal intensity contour of the *NGC*6251 nuclear jet with the cometary isophotes, one readily notices a similarity between the two. The underlying physical process in the cometary case is somewhat different. Evaporating molecules are ionized by solar radiation, which is an important factor in the case of cometary solar wind interaction. Again, the gravity of cometary nucleus is neligible. Nevertheless, one may expect that the over-all picture remains almost the same in the two cases. The essential phenomenon is the behaviour of the gas outflow immersed in a supersonic stream.

7. Comparison with other models

Galactic jets which have been closely investigated so far are one sided. The radio jet *NGC*6251, the optical jet *M*87 and the optical jet 3C237 are all one sided. Thus, any hypothesis on galactic jets ought to be consistent with this observed result. The luminosity L_1 of a jet streaming toward the observer is related to the luminosity L_2 of a hypothetical counter jet (if it existed) by the relation that[26)]

$$\frac{L_1}{L_2} = \left[\frac{1+u\sin\theta/c}{1-u\sin\theta/c}\right]^{3+\alpha}$$

where c is the velocity of light, and α is the spectral index which is approximately 0.5 for most jets; θ is the angle between the jet and the plane which is perpendicular to the line of sight. For the hypothetical counter jet to remain unobservable, it is necessary that $u \sim c$ *and* $\theta \geq 60°$. Unless these two conditions are simultaneously satisfied, one should expect to observe two jets emerging from a galaxy or a quasar.

The bubble model of extended radio sources by Gull & Northover can gain at most 10^3kms^{-1} even if a massive galaxy ($3 \times 10^{13} M_\odot$) immersed in a dense (1.3×10^{-27}gcm^{-3}) intraculster gas is assumed. The model fails to account for the fact that only one jet has been observed in most cases.

The twin exhaust model of Branford & Rees[4) assumes that hot gas at the nuclear region of a galaxy is accelerated to a relativistic speed by flowing through two de Laval nozzles. Since the flow is relativistic, one of the requirements mentioned above ($u \sim c$) is satisfied. It remains to explain why θ is large in almost all cases. In the accretion wake hypothesis, the jet is always one sided. A counter jet, if observed, will be a strong case againts it.

According to the accretion wake model, the *V* shaped radio source (3c 465) is to be ascribed to two wakes, each caused by a single galaxy. There is a double galaxy at the vertex of the *V* shaped source. Thus, the radio source can be ascribed to two galaxies which happen to have come close to each other in a dense intergalactic medium.

As to the accretion column, Cowie[27) investigated the stability in a case where pressure is entirely neglected (cold accretion). By the WKB approximation, he showed that the column is unstable to short wave-length perturbation. However, inclusion of pressure is likely to stabilize the short wave-length perturbation. We have also assumed that the theory of line accreation is valid for the values of Mach number which are relevant in the application to the galactic jets. This assumption should be tested by a more detailed investigation. Hunt[24) carried out a fully fluid dynamical study of the accretion process for $M_\infty \sim 1$. A similar study for larger values of M_∞ appears to bc needed. These are problems which need to be clarified.

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