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EQUIPARTITION JET MODEL FOR THE SEYFERT 1 GALAXY 3C120

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ABSTRACT

The motion of 3C120 Jet relative to the core is reasonably uniform and the VLBI scale jet connects outwards to a VLA $\sim$ 100 kpc scale. We measured the jet width variation from the center and found some indication of a power law which indicates the jet expands roughly with a constant opening angle and a constant flow velocity, $V_f \cong c$, from subparsec scales to $\sim$ 100 kpc. With such a constant flow velocity and based on other physical parameters deduced from observed emission characteristics of the jet, we have established an equipartition jet model which might accommodate the basic parameters of the jet on subparsec scales, with which one can fit the radio intensities over all the scale of the jet even to $\sim$ 100 kpc.

Keywords: galaxies, 3C120, jet, radio sources, synchrotron emission

1. INTRODUCTION

The radio source 3C120 (II Zw 14) is a relatively nearby seyfert 1 extra-galaxy at a redshift of 0.033 and it is one of the first sources in which apparent superluminal motions were found with very long baseline interferometer (VLBI) observations. This superluminal motion of jets is known as a projection effect of relativistic collimated outflows of the core region plasma of an active galactic nucleus (AGN). The optical image of the galaxy is about 1′ in extent and its nucleus is a strong and variable source of radiation at all observed wavelengths from radio to X-ray. For H_o = 100 h km s^{-1} Mpc^{-1} and $q_o = 0$, one milliarcsecond (mas) corresponds to 0.46 pc (h=1) and an observation of proper motion of 1 mas yr^{-1} corresponds to a speed 1.5 h^{-1}c. Recently Gomez et al. (1998) found 100 superluminal components with angular velocities 1.5 – 3.6 mas yr^{-1} which correspond to 2.3 – 5.5 h^{-1}c, about 5 times the speed of light!

How the jet in AGN nucleus would be emerged from the center and be collimated still remains unclear. Eggum et al. (1985) proposed the main part of this work was done while the author was in UCLA that the ray is formed due to an accretion disk in the inner most area: the matter streaming into the center creates a shock and pushes the plasma gas along the axis direction above the disk and eventually develops a corona gas (see also Blandford & Rees 1974 and Hyung et al. 2000). This corona is accelerated either by 'radiation' or 'gas pressure' along the axis and the so-called collisionless magnetic field will collimate the plasma into a ray and create a jet pair. Another possibility is that a 'rotating black hole' in the magnetic field acts as a dynamo and produces a potential gradient along the axis, so the particles will be accelerated, which will be again collimated to a form of ray

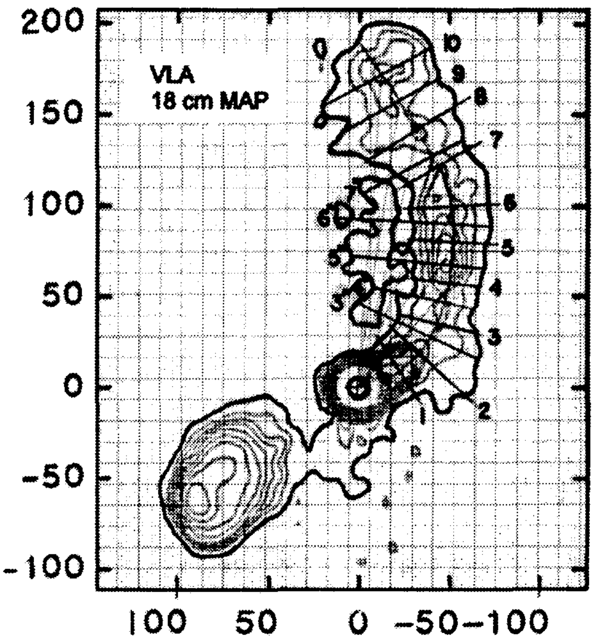

Figure 1. Jet width vs distance from core. The distance from the core is not corrected for projection, so we let $\sin i = 1$. Opening angle $\theta = 16.^{\circ}53$.

by magnetic fields. According to the structure, jets are classified either core or lobe domated and its spectrum is mainly due to synchrotron radiation, $I_\nu = \nu^{-\alpha}$. With better spatial resolution and sensitivity radio telescopes, one now could investigate their structures. However, there are still many unknown basic questions to the superlimininal sources and AGN jet structure, mainly due to various difficulties in measuring proper motions and unknown orientation angle of jets (Homan et al. 2001).

Most VLBI sources consist of an unresolved self-absorbed part (the *core*) and a steep-spectrum jet on one side only. Based on the VLBI and VLA radio maps, we establish the basic parameter of the jet assuming a free jet with a constant opening angle. The ejection which occurred in both direction supplied energy to the extended double sources, but the receding components would be greatly dimmed by special relativistic effects, while approaching components were brightened. 3C120 consists of a pair, but we use the well observed approaching jet component. There exist more recent radio obervational data, e.g. 6-cm radio data by Walker (1997) or other 22 and 43 GHz radio data by Gomez et al. (1998). However, since we are not interested in measuring the proper motion, these recent 6-cm data or other addition of data will not be very helpful for our study. We use the 6-cm (5 GHz) and 18-cm radio data by Walker (1986) or Walker et al. (1987). In a similar way as done in the earlier theoretical works, e.g. by Blandford & Kognigl (1979), we will examine a few models with which one might explain the relativistic outflow characteristics of 3C120 jet based on a crude approximation and somewhat idealized simple geometry.

2. OBSERVATIONAL DATA

The radio source 3C120 was mapped on scales from 1 pc to 400 kpc by Walker (1986) and also

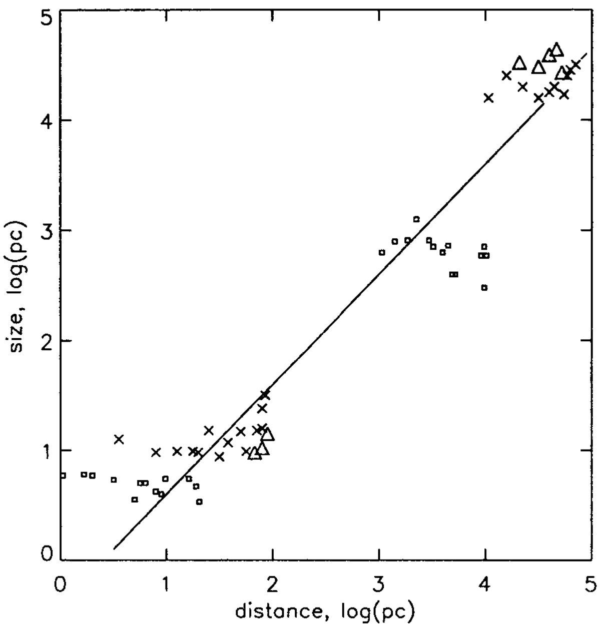

Figure 2. Jet width vs distance from core. VLBI 6-cm (o); VLBI 18-cm (×); VLA 6-cm (o); and VLA 18-cm (×); uncertain (△). The distance from the core is not corrected for projection, so we let $\sin i = 1$. Opening angle $\theta = 16.^{o}53$.

by Walker et al. (1982, 1984, 1987). The observations show that the jet is continuous from the parsec scales to over 100 kpc (for $H_o = 100$ h km s^{-1} Mpc^{-1}, 1 arcsecond is 455 pc; we will assume h = 1, hereafter); superluminal motions are seen on parsec scales as mentioned earlier. The wide range of scales show a power-law function of central-jet brightness vs distance from the core. From the 5 GHz measurement of, for example, Walker (1986), we note that its peak intensity of the 3C120 Jet is varying as a function of distance from the core: the power law of the central intensity has an index of -2.2 [$I_\nu(x) = 1/x^{2.2}$ for a normalized distance x], and the spectral index is measured about α = -0.7 ($I_\nu = \nu^{-\alpha}$). Here, the normalzed distance $x = Z/Z_o$ ($Z_o = 1$ pc) was not corrected for the curve of the jet or for projection on the sky.

We have chosen the 4 best maps from sequence of Walker's radio map of 3C120 on both scales, VLBI and VLA. Table 1 lists the jet widths vs distances from the center for the VLA 6- & 18-cm and VLBI 6- & 18-cm contour maps. Figure 1 shows schematically how we measured the distance from the center and jet width from the Walter's 18-cm VLA radio map. Here, we do not present the other VLA and VLBI drawings given in Table 1.

The arcsecond and larger scale structures in 3C120 are very weak relative to the core. Between these two distance scales, kpc (VLA) and pc (VLBI), there is no physical evidence that the jets actually connect. However, the continuity and the simple behavior of the brightness suggest that the basic parameters of the jet are established on subparsec scales and evolve in a relatively simple manner out to 100 kpc (Walker 1986). Figure 2 shows the logarithmic diagram of the jet width, D(z), versus projected distance, Z, from the core based on Table 1 data. In some parts of jet, however, the outer edge of the contours of the jet is questionable (△), and there is no data between kpc scale

Table 1. Jet width measurements from VLBI and VLA maps by Walker (1986) and Walker et al. (1987).

VLBI 6 cm-Map Z (pc)	(0.05″/20 pc) width (pc)	VLA 6 cm-Map Z (kpc)	(25″/10 kpc) width (kpc)
0.7	6.4	1.1	0.6
1.8	5.9	1.4	0.8
2.3	5.8	1.9	0.8
3.4	5.0	2.3	1.2
5.2	3.6	2.8	0.8
5.8	4.6	3.2	0.7
7.1	4.9	3.7	0.6
8.4	4.2	4.2	0.8
9.0	3.9	4.6	0.4
9.8	5.4	5.1	0.4
15.5	5.4	9.0	0.6
19.8	4.5	9.4	0.3
21.2	3.4	9.8	0.7
-	-	10.2	0.6
VLBI 18 cm-Map Z (pc)	**(0.3″/120 pc) width (pc)**	**VLA 18 cm-Map Z (kpc)**	**(200″/80 kpc) width (kpc)**
3.8	12.3	11.1	14.1
8.5	9.5	15.3	21.7
12.3	9.5	22.2	17.6
17.0	9.5	31.0	14.8
21.7	9.5	38.4	16.6
26.0	14.2	44.4	17.6
28.8	8.5	51.8	15.3
35.9	11.3	58.3	22.7
41.6	11.3	62.9	24.0
46.8	14.2	68.9	27.3
52.0	9.5	22.2	28.7(Δ)
70.9	13.2	31.0	26.4(Δ)
75.6	15.1	38.4	29.6(Δ)
79.4	24.6	44.4	34.2(Δ)
86.9	32.1	51.8	25.0(Δ)
72.8	9.5 (Δ)		
81.3	10.4(Δ)		
86.9	14.2(Δ)		

(Δ): points are where the outer edge of the jet is not clear.

VLA-map and pc scale VLBI-map. Even though it is difficult to find any regular variation of the jet size, D(z), from VLA or VLBI data by itself, we can have some indication of a power law, $D(z) \sim D_o \left(\frac{Z_o}{Z}\right)^{-1}$, which means the jet expands with a constant opening angle. If the jet expands with a constant opening angle θ, tan $\theta = \frac{C_f}{V_f} = \frac{1}{M_f}$ = constant; for a flow velocity, V_f = constant & sonic Mach number M_f, the radius of the jet expands with internal sound speed $C_f = \sqrt{\frac{\gamma T}{m_f}}$ = constant (for particle mass m_f & temperature T), or vice versa.

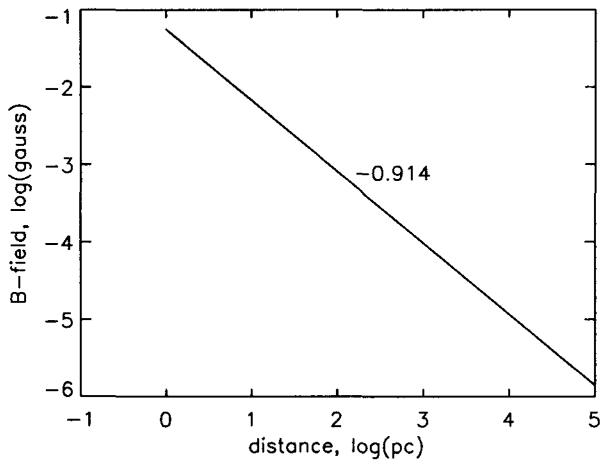

Figure 3. Equipartition magnetic field variation. The magnetic field of the 3C120 Jet as a function of distance from the core varies like toroidal field ($B_\phi \sim \frac{1}{x}$).

3. MODEL

The measured central brightness distribution of the jet as a function of distance from the core, $I_\nu(x) = 1/x^{2.2}$, represents a strong constraint on any jet model. The brightness of the jet is a function of its size, magnetic field, density of relativistic electrons, and bulk velocity. We have constructed the simplest possible model. First, we have started with a possibility on whether 3C120 is adiabatic or not.

3.1 Adiabatic jet

As seen in Figure 2, there is an indication of a power law, $D(z) \sim D_o \left(\frac{Z_o}{Z}\right)^{-1}$, which indicates the jet expands with a constant opening angle. To represent the jet geometry, we introduce some variables: an initial distance Z_o where the jet width is D_o. We assume the jet is expanding with a constant angle. The jet starts at initial distance, Z_o, with a certain size (or width), D_o, so that the width of jet at any distance, Z, from the core, is

$$D(z) = D_o \frac{Z}{Z_o}, \tag{1}$$

and we will let $x = \frac{Z}{Z_o}$ and $l(x) = D(z)$. We will adopt $D_o = 0.39$ pc at $Z_o = 1$ pc. We will simplify our problem by assuming that the jet contains only relativistic particles (mainly electrons). In this case, if the flow velocity is constant, then proper density varies like $n(x) \sim \frac{1}{x^2}$. Hence, we let

$$n(x) = n_o \left(\frac{Z_o}{Z}\right)^a = \frac{n_o}{x^a}, \tag{2}$$

where a is constant (for $D(z) \propto Z$, $a = 2$).

Proper magnetic field also varies according to a power law ($B_{||}(x) \sim \frac{1}{x^2}$, $B_\perp(x) \sim \frac{1}{x}$ from

$\nabla \cdot B = 0$), thus, we assume magnetic field varies like

$$B(x) = B_o \left(\frac{Z_o}{Z}\right)^b = \frac{B_o}{x^b}. \tag{3}$$

If the jet is adiabatic ($\frac{P}{n^\Gamma}$ = constant, $\Gamma = 4/3$) and the particle distribution is isotropic, then the relativistic Lorentz factor of the particles' thermal motion scales as

$$\gamma \propto n^{1/3} = n_o^{1/3} \left(\frac{Z_o}{Z}\right)^{\frac{a}{3}} = \frac{n_0^{1/3}}{x^{\frac{a}{3}}}, \quad \gamma_{10} \leq \gamma \leq \gamma_{20}\ (\gamma_{10} \ll \gamma_{20}). \tag{4}$$

Meanwhile, normalized distribution function of electron will be given as

$$f(\gamma) = \frac{2\alpha n}{[1 - (\gamma_1/\gamma_2)^{2\alpha}]\gamma^{2\alpha+1}}, \quad \gamma_1 \leq \gamma \leq \gamma_2\ (\gamma_1 \ll \gamma_2). \tag{5}$$

So, volume emissivity of the synchrotron radiation, $\epsilon_{\nu'}$, at any comoving frequency(ν') is

$$\epsilon_{\nu'} = \frac{2}{3} K \frac{c\sigma_T B^2}{8\pi} \frac{2\alpha n \gamma_1^{2\alpha}}{(1 - (\gamma_1/\gamma_2)^{2\alpha})\nu_s'} \left(\frac{\nu_s'}{\nu'}\right)^\alpha; \quad \nu_s = \frac{3}{2} f_c. \tag{6}$$

where f_c is the cyclotron frequency, and K is a constant. Eventually, this will become

$$\epsilon_{\nu'} = \frac{K'\mathcal{D}^\alpha}{\nu^\alpha} \frac{1}{x^{a+b+(2a/3+b)\alpha}}. \tag{7}$$

where K' is a constant and Doppler boosting factor $\mathcal{D} = \gamma^{-1}(1 - \beta \cos i)^{-1}$.

The surface brightness, $I_\nu(x)$, which is what we measure, should then scale as

$$I_\nu(x) = \frac{\epsilon_{\nu'} l(x)}{4\pi} = \frac{K''\mathcal{D}^\alpha}{\nu^\alpha} \frac{1}{x^{a+b-1+(2a/3+b)\alpha}}, \tag{8}$$

where K'' is a constant. Here, we assumed a conical jet shape. On the other hand, the observed peak intensity of the 3C120 Jet shows the following power law (Walker 1986),

$$I_\nu(x) \propto \frac{1}{x^{2.2}}. \tag{9}$$

Now, the question is whether or not the model can match the observed value, that is, $a + b - 1 + \left(\frac{2a}{3} + b\right)\alpha \stackrel{?}{=} 2.2$, where '?' means questionable and $\alpha = 0.7$ (or $\alpha = 0.65$). For $a = 2$ and $b = 1, a + b - 1 + \left(\frac{2a}{3} + b\right)\alpha \simeq 3.63 > 2.2$, and any reasonable values of a and b ($a \approx 2$, $1 \leq b \leq 2$), the adiabatic model cannot predict the observed dependence of I_ν on Z. Furthermore, the adiabatic jet cannot emit $\nu = 5 \times 10^9$ Hz radio radiation over all the length of the jet, since the adiabatic decrease of γ_2 and the decrease in magnetic field strength results in the characteristic synchrotron frequency decreasing below 5 GHz.

3.2 Equipartition jet

Probably the estimate of the magnetic field from the energy equipartition condition is the only way of estimating the magnetic fields in 3C120. From the knowledge of simple geometry and total brightness distribution of the source we have evaluated the magnetic fields variation along the jet. We show in Appendix I that the magnetic field for the equipartition jet scales as

$$B(x) = \frac{B_o}{x^{0.914}}, \quad \text{where } B_o \cong 5 \times 10^{-2}(\text{gauss}) \ at\ 1 \text{ pc}. \tag{10}$$

Figure 3 shows the magnetic field variation along the jet, i.e. $B(x) \sim x^{-.914}$. Since magnetic flux conservation implies that axial fields decrease as $\sim x^{-2}$ and azimuthal field, scale as $\sim x^{-1}$, we conclude that the equipartition field must be primarily azimuthal. If the jet expands at constant opening angle and has a constant flow velocity, then the density of the jet, $n(x)$, varies like

$$n(x) \propto \frac{1}{x^2}. \tag{11}$$

If equipartition holds along the jet, the relativistic particles must accelerate according to

$$\gamma_1 = \gamma_{1o} x^{0.17} \simeq \text{constant.} \quad \text{(see Appendix I)} \tag{12}$$

Even though the details of this acceleration process is difficult to explain, the equipartition jet can radiate $\nu = 5 \times 10^9$ Hz radio emission all along the jet. From the observed radio frequency $\nu = 5 \times 10^9$ Hz and synchrotron radiation argument along the jet, we have estimated the minimum and maximum values, $\gamma_1 \approx 10^2$ and $\gamma_2 \approx 10^4$, respectively (Appendix II). For the equipartition model, we now examine whether synchrotron losses are significant and consider the electron heating rate which is required in order to maintain the equipartition electron energy density against adiabatic expansion losses.

3.2.1. Synchrotron losses

Relativistic electrons that are emitting synchrotron radiation lose energy at a loss rate

$$-\left(\frac{dE}{dt}\right)_s = -m_e c^2 \frac{d\gamma_1}{dt} = \frac{4}{3}\frac{c\sigma_T B_o^2 \gamma_1^2}{8\pi x^2}, \tag{13}$$

where $\frac{d}{dt} = \frac{\partial}{\partial t} + V_f \frac{\partial}{\partial x}$. Then we have

$$\frac{mc^2 c\beta}{Z_o}\frac{\partial \gamma_1}{\partial x} = -\frac{4}{3}\frac{c\sigma_T B_o^2 \gamma_1^2}{8\pi x^2}, \tag{14}$$

This loss rate is especially important for very high energies, and it also has a dependence on the distance parameter x from the central source. For the equipartition scalings, we can integrate the energy loss as

$$\int_{\gamma_{1o}}^{\gamma_1} \frac{1}{\gamma_1^2} d\gamma_1 = -\frac{4}{3}\int_1^x \frac{\sigma_T B_o^2}{8\pi x^2} dx, \tag{15}$$

or

$$\gamma_{1,2} = \frac{\gamma_{1o,2o}}{1 + \frac{4}{3}\left(\frac{\sigma_T Z_o B_o^2 \gamma_{1o,2o}}{8\pi m_e c^2}\right)\left(\frac{x-1}{x}\right)}. \tag{16}$$

By substituting equipartition magnetic field B_o which we obtained at $Z_o = 1$ pc, we have

$$\frac{4}{3}\left(\frac{\sigma_T Z_o B_o^2 \gamma}{8\pi m_e c^2}\right) = 3.24 \times 10^{-5}\gamma. \tag{17}$$

Therefore, synchrotron losses of electrons in the range of $\gamma = 10^2 - 10^4$, are negligible.

3.2.2. Adiabatic losses

Relativistic electrons in a synchrotron source can also lose energy due to adiabatic expansion of the radiating region. Our assumption was that flow velocity of the jet, V_f, is constant, and therefore,

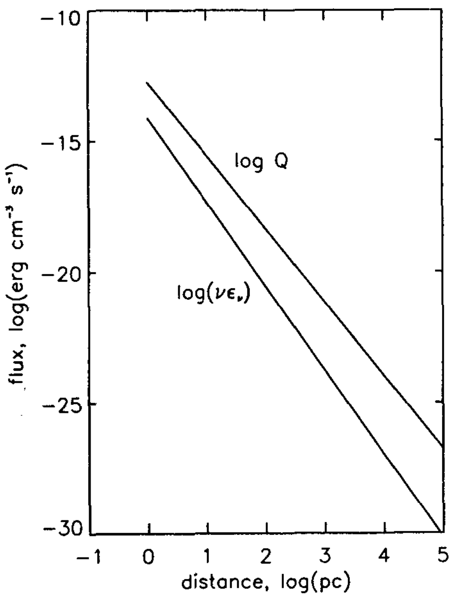

Figure 4. Heating rate, Q and $\nu\epsilon_\nu$. When the jet is moving outward, expansion against external pressure cause heating (Q).

density of the jet varies like $n \sim \frac{1}{x^2}$. In Sec. 2, we also found that the 3C120 Jet has an approximately constant opening angle. As far as total pressure is concerned, the equipartition jet basically remains isothermal (constant γ_1), since $n(x) \sim \frac{1}{x^2}$ and $B(x) \sim \frac{1}{x}$. Thus, if the jet is pressure confined by an external medium, the jet will lose its energy adiabatically by doing work against the external pressure ($\frac{P}{n^\Gamma}$ = constant, $\Gamma = 4/3$).

Since $n(x) \sim \frac{1}{x^2}$, the internal pressure would vary $P(x) = \frac{1}{3}u_p(\sim n^\Gamma) \sim \frac{1}{x^{2\Gamma}}$ under the adiabatic assumption. Then we have pressure variation which does not agree with equipartition variation,

$$\frac{1}{x^{2.67}} \sim P(x) < \frac{B(x)^2}{4\pi} \sim \frac{1}{x^{1.83}}. \tag{18}$$

Hence the equipartition jet cannot be adiabatic, and the run of brightness as a function of x will be sub-adiabatic. Otherwise the expansion would soon produce departures from equipartition.

Hence, in order to maintain equipartition, heat must be added. However, if this heat is significantly lost by radiation or by any other processes, this jet cannot maintain its equipartition condition.

3.2.3. Calculation of heating rate, Q

For equipartition, we can calculate a heating rate, Q = $\frac{d}{dt}(Adiab)$, and will be able to compare the heating rate with the synchrotron loss rate $\nu\epsilon_\nu$ at each x. The heating rate, Q, of this pressure confined equipartition jet by adiabatic expansion can be defined as

$$Q \equiv \frac{1}{\Gamma - 1}\left[\frac{dP}{dt} - \frac{\Gamma P}{n}\frac{dn}{dt}\right], \tag{19}$$

where $P = \frac{1}{3}u_p = \frac{1}{3}nmc^2\gamma$, $\Gamma = \frac{4}{3}$ and $\frac{d}{dt} = \frac{\partial}{\partial t} + V_f\frac{\partial}{\partial x}$. Since $n(x) \sim \frac{1}{x^2}$ and γ_1 = constant, the heating rate is

$$Q = -\frac{\beta c}{Z_o}\left[\frac{mc^2\gamma_1}{3}\right]\frac{\partial n}{\partial x} = \frac{2}{3}\frac{\beta mc^3\gamma_1}{Z_o}\frac{n_o}{x^2}$$

or,

$$Q \cong 4.9\times 10^{-14}\frac{\gamma_1 n_o}{x^3}(\mathrm{erg/cm^3/sec}), \quad (20)$$

where $V_f = \beta c$, and $\beta = \mathcal{O}(1) \sim 1$. The observed central brightness per unit volume is given as

$$\nu\epsilon_\nu \cong \frac{6.6\times 10^{-15}}{x^{3.2}}(\mathrm{erg/cm^3/sec}). \quad (21)$$

From u_p and u_m at 1 pc, we can evaluate $n_o\gamma_1$, by setting

$$\left(\frac{2\alpha}{2\alpha-1}\right)n_o mc^2\gamma_1 = \frac{B^2}{8\pi}, \quad (22)$$

so we have $n_o\gamma_1 = 3.47$. Now, we can compare Q and $\nu\epsilon_\nu$. Figure 4 shows that heating rate of the equipartition jet for 3C120 is much greater than the observed central brightness all along the jet,

$$Q \gg \nu\epsilon_\nu. \quad (23)$$

Hence we can conclude that only a small fraction of the heating rate is lost by radiation of the jet, so that all the heat is going into doing work against external pressure.

4. DISCUSSION

So far, we have discussed the central brightness distribution of 3C120 by checking two possibilities. One model was to assume that the jet is adiabatic; however the adiabatic model cannot easily explain the observed dependence of I_ν on distance. The second model assumed that jet maintained equipartition; this model can possibly explain the power law of central brightness distribution vs distance from the center. Due to the aberration angle of jet expansion, i, relative to the observer, the synchrotrotron intensity of jet could be boosted by a factor of $\left(\frac{1+(V_f/c)\cos i}{1-(V_f/c)\cos i}\right)^{2+\alpha}$. When we measured jet widths, however, such a projection angle is not considered, that is, we assumed $i \sim 90^o$. This is not true in real situation, since a superluminal velocity can be defined as $v_p = \frac{V_f \sin i}{1-(V_f/c)\cos i}$ for a small i and $V_f = \mathcal{O}(c)$ and there exists a superluminal motion of $v_p = 2.3 - 5.5\ h^{-1}c$ in a subparsec or parsec scale of 3C120. Thus, our model is very schematic although we started with some basic parameters obtained from the observations. Consideration of such a projection is beyond the scope our investigation.

Our results show that if the jet is free, then $\gamma \sim$ constant; if $\beta_f \simeq$ constant, $n \sim \frac{1}{x^2}$; and if $B(x) = B_\phi$, $B(x) \sim \frac{1}{x}$. The equipartition jet may not lose its energy by any other way. However, if the 3C120 Jet is pressure confined, the maintenance of equipartition requires that the jet dissipates a large quantity of energy in order to replace the expansion energy losses. The details of equipartition processes are largely unknown, and still unknown as well is whether they are able to maintain equipartition or not. Since the merit of equipartition is to evaluate the minimum energy required for the observed synchrotron radiation, it is generally assumed as a working hypothesis. Although the required high dissipation rate is possible, the fact that Q greatly exceeds the synchrotron loss rate is suspicious.

Ghisellini et al. (1993) observed 105 sources and found an evidence of superluminal motions in 39 of them. They concluded that typical Lorentz factor of jets was $\gamma = 10$ (rather somewhat smaller)! Walker (1997) reanalyzed the 4″ knots of 3C120 including the earlier epochs data and concluded this kpc scale knot was more slowly moving than the parsec scale features. The speed measured from the structural variation, however, does not necessarily equal to the flow speed. Although it is really a difficult job to detect jet movement, our model implies a rather high $\gamma = 70 - 10^4$ (Appendix II), though! In Sec. 2 we found that from VLBI to VLA scales the jet radius expands with an approximately constant opening angle. If the external pressure is much less than the jet's internal pressure, the jet radius expands freely at the internal sound speed; hence, for a constant flow speed, the opening angle is constant and inversely proportional to the sonic Mach number. Since no work is done against the external pressure, the jet remains isothermal. Hence if the jet is in equipartition on the VLBI scale, a free jet will remain in equipartition. Since the equipartition scalings yielded a reasonable explanation for the observed dependence of the brightness, I_ν, on distances, we conclude that the most likely model for 3C120 is that the jet is free.

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APPENDIX I. Equipartition Model

With regard to the spectra observed from synchrotron source, the emission is in the form of discrete multiples of the cyclotron frequency (f_c),

$$\nu_s = \frac{3}{2} f_c = B(\frac{4.2\text{GHz}}{\text{gauss}}), \tag{1}$$

where the characteristic synchrotron frequency is $\nu = \nu_s \gamma^2$. The energy in the source has two components, relativistic electron energy and magnetic field energy density. The energy of relativistic particles in volume, V, is

$$E_p \simeq \frac{mc^2 8\pi}{(4/3)c\sigma_T B^2} \sqrt{\nu_s} \int_{\nu_s}^{\infty} \frac{V\epsilon_\nu}{\sqrt{\nu}} d\nu, \tag{2}$$

and the energy in the magnetic field is

$$E_m = \frac{B^2}{8\pi} V. \tag{3}$$

Considering that total energy of the source must be constant, if we raise magnetic field, we need a lower energy for the electrons. Conversely, if there is a low magnetic field in the source, then the particle energy goes up. Thus, somewhere in between, there has to be a minimum which is almost the same result obtained by setting the particle energy equal to the magnetic field energy. By equating two equations, $E_p = E_m$, we can find equipartition magnetic fields. If the equipartition magnetic field is given as (which is the same as before),

$$B(x) = \frac{B_o}{x^b}, \tag{4}$$

the volume emissivity can be evaluated as;

$$\epsilon_\nu = 4.68 \times 10^{-20} \frac{B_o}{x^{3b/3}}. \tag{5}$$

Since the power law of 3C120 has an index of -2.2, we expect a proportionality,

$$I_\nu = \frac{\epsilon_\nu l(x)}{4\pi} \overset{expect}{\longrightarrow} \propto \frac{1}{x^{2.2}}. \tag{6}$$

Then we have a model which consists with the observed power law, in case when $b = 0.914$ and $B_o = 5 \times 10^{-2}$ gauss at $Z_o = 1$ pc. From eq. (4), the equipartition field varies like $B = B_o \left(\frac{Z_o}{Z}\right)^{0.914}$. Electron number density is given by

$$n = N \int_{\gamma_1}^{\gamma_2} \frac{dr}{\gamma^{2\alpha+1}}, \tag{7}$$

where the normalization factor is

$$N = \frac{2\alpha n \gamma_1^{2\alpha}}{1 - (\gamma_1/\gamma_2)2\alpha}, \quad (2\alpha + 1 > \frac{1}{2}, \ \gamma_1 \ll \gamma_2). \tag{8}$$

The relativisitc particle (electron) energy density is

$$u_p = mc^2 N \int_{\gamma_1}^{\gamma_2} \frac{\gamma d\gamma}{\gamma^{2\alpha+1}} = \left(\frac{2\alpha}{2\alpha - 1}\right) \frac{nmc^2\gamma_1}{1 - (\gamma_1/\gamma_2)^{2\alpha}} \left(\frac{1}{1 - (\gamma_1/\gamma_2)^{2\alpha-1}}\right) \simeq nmc^2\gamma_1, \tag{9}$$

where $\gamma_1/\gamma_2 \ll 1$. The magnetic field energy density is

$$u_m = \frac{B^2}{8\pi}. \tag{10}$$

Letting $u_p = u_m$ [equations (9) & (10)], and if the flow velocity V_f = constant, $n(x) \sim \frac{1}{x^2}$ (from $V_f R(z)^2 n$ = constant), then all along the jet

$$\gamma_1(x) = \gamma_{1o} x^{0.17} \simeq \text{ constant}. \tag{11}$$

APPENDIX II. Synchrotron Radiation

The characteristic synchrotron frequency is

$$\nu = \frac{3}{2} f_c \gamma^2 = 4.2 \times 10^6 B \gamma^2. \tag{12}$$

As in Figure 3, the magnetic field varies as,

$$B(x) = \frac{5 \times 10^{-2}}{x^{0.914}}. \tag{13}$$

To observe 5 GHz radio emissions at Z_o = 1 pc, since we know equipartition magnetic field there, it requires

$$\nu > 10^9 = 4.2 \times 10^6 \, \frac{5 \times 10^{-2}(\text{gauss})\gamma_1^2}{1^{0.914}}, \tag{14}$$

which gives γ_1 = 69.01. On the other hand, the electrons of γ_1 at $Z_{\max}$ = 10 kpc will probably radiate the lowest synchrtron radiation

$$\nu_{low} = 4.2 \times 10^6 B(x) \gamma_1^2 = 2.19 \times 10^5 \text{ Hz}. \tag{15}$$

In order to observe 5 GHz emission at Z_{max} = 10 kpc (see Figure 3), where high energy electrons in low magnetic fields, we require that γ_2 satisfies

$$\nu = 5 \times 10^9 \text{Hz} = 4.2 \times 10^6 \gamma_2^2 \; (1.1 \times 10^{-5} \text{ gauss}), \tag{16}$$

which gives γ_2 = 1.04×10^4. At Z_o = 1 pc, electrons of γ_2 will radiate the highest energy synchrotron radiation

$$\nu_{high} = 4.2 \times 10^6 B(x) \gamma_2^2 = 2.29 \times 10^{13} \text{ Hz}. \tag{17}$$