



2010-1

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## Recommended Citation

Spicer, D. S., Bingham, R. and o'Sullivan, S. A model for predicting extragalactic jet lifetimes. *Journal of Plasma Physics* / Volume 76 / Issue 02 / April 2010, pp 129-134. DOI: <http://dx.doi.org/10.1017/S0022377809990730>

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Letter to the Editor

# A model for predicting extragalactic jet lifetimes

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(Received 6 October 2009 and accepted 1 December 2009, first published online 15 January 2010)

**Abstract.** In this letter, we propose a model to explain the disintegration of extragalactic jets and to predict the associated timescale. The model assumes that a jet is current and charge neutral as well as collimated at its source; however, the forward electron current gradually decays producing a magnetic field transverse to the direction of jet propagation. This growing transverse magnetic field eventually causes the jet to disintegrate.

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## 1. Introduction

In this letter, we describe a new approach to model extragalactic jet propagation; the model considers plasma turbulence providing anomalous collisions that are found to be much more effective in controlling jet dynamics than classical collisions. Classical collisional ion stopping in cold matter (the ambient extragalactic medium) shows that a proton with a conservative estimate of energy of 4.8 MeV has a range of  $\simeq 100 \text{ mg cm}^{-2}$  [1]. As the ambient extragalactic medium number density is roughly  $10^{-4} \text{ cm}^{-3}$ , the stopping distance of a proton of 4.8 MeV energy is  $\simeq 200 \text{ Mpc}$ . It therefore follows that protons with energies of  $\gamma \geq 5$  will go even farther. Also, as an ion will deposit the bulk of its energy near the end of its stopping range [1], little energy will be lost because of classical collisions, nor will there be much slowing of the ion, between the beginning of the jet and its termination point. Clearly, a jet is not a single proton or ion but a beam of them, together with the requisite 'forward' electron current needed to ensure current neutrality (without a forward current to provide current neutrality the jet will be destroyed very near its origin; see below). However, because jets appear to be 'low intensity' beams in that the constituent particles do not interact with one another over much of a jet's range nor does the jet radically alter the ambient plasma through which it

propagates (for example through strong heating), it is safe to argue that the jet ions are behaving ballistically for all intents and purposes.

Even though the stopping distance for  $\gamma \geq 5$  is well in excess of the maximum distance jets are known to propagate, there is one additional mechanism that can further increase the jet's potential range even beyond which we have calculated above: because the jet's velocity is much greater than its own thermal velocity and the thermal velocity of the ambient plasma through which it propagates, it is very likely that two-stream instabilities will occur at the nose of the jet. These instabilities are powerful mechanisms for providing strong momentum and energy coupling between the streaming jet ions and electrons with their counterparts in the ambient medium [2]. When this occurs a 'snow-plow' effect will result, causing the ambient medium to be pushed out of the way of the jet particles behind the jet's nose, so that the jet effectively bores a hole right through the ambient medium. This means that the jet is truly moving ballistically. Hence, the only real interaction between the jet and the external environment except at the jet's nose is at the edges of the jet.

An additional argument often used to justify a fluid model relies on the invocation of turbulent magnetic fields entrained within the jet. Given the  $\gamma$ 's often quoted for extragalactic jets, this argument seems to miss the mark. Turbulent magnetic fields will of course increase the effective cross-section for scattering if the magnetic field strengths are large enough, thereby reducing the mean-free path. However, the contradiction in this argument is that although turbulent fields will cause enhanced collisionality and therefore make the jet more fluid like, this same enhanced collisionality will reduce the range a jet can propagate. In addition, to really affect ions with  $\gamma \geq 5$ , the magnitudes of the turbulent magnetic fields needed must be quite large. In a turbulent medium, magnetic fields can be expected to possess a spectrum of wavelengths,  $\lambda$ . Only long wavelength components of the spectrum will have any real effect on the jet propagation and they must be of order  $\lambda \approx R$  (the radius of the jet), something that is unlikely because of causality. The magnitude of the deflection,  $\Delta r$ , of jet ions encountering a magnetic field normal to the jet direction will of order  $\lambda^2 r_g^{-1}$ , where  $r_g \approx 31.6(\gamma A\beta/Z\delta B)$  km is the relativistic gyroradius of a jet particle; hence, the deflection scales as  $\Delta r \sim R^2 Z\delta B/\gamma A\beta$ , where  $A$  is the atomic number of the particles making up the jet,  $Z$  is its charge state and  $\delta B$  is the magnitude of the turbulent magnetic field present. Clearly, the higher the jet energy the less effective the scattering, unless the magnitude of  $\delta B$  is large along the entire jet, much larger than observations can support.

Although there are many models for the production of extragalactic jets, they all share three things in common: they assume outflows that are collimated, current neutral and charge neutral. However, an overlooked aspect of jet current neutrality is that it is not necessarily permanent and that the loss of current neutrality can, in our opinion, naturally explain the disintegration of a jet after it has propagated long distances. The basic mechanism that causes the jet to disintegrate in our model is quite simple; the jet slowly loses current neutrality as it propagates, until the self-magnetic field produced causes the jet particles to acquire a transverse component of momentum so large that their gyroradii become of the order of the jet radius and propagation is inhibited.

## 2. Jet stability

Our analysis makes the following two assumptions: the standard model of an extragalactic jet resulting from the outflow of neutral plasma is appropriate, i.e.

the jet is both charge and current neutral, at least initially, and the jet is already collimated with low jet emittance, that is,  $|v_{J\perp}| \ll |v_{J\parallel}|$ , where  $v_{J\perp}$  is the magnitude of the jet velocity perpendicular to its direction of propagation and  $v_{J\parallel}$  is the magnitude of the jet velocity parallel to its direction of propagation. Physically, the first assumption implies that electrons are dragged along by the jet ions in the form of a forward electron current ensuring current neutrality with the same speed  $v_{J\parallel}$ , and number density as the ions. However, because of the large ion-to-electron mass ratio,  $m_i/m_e$ , the electrons have an energy less than the ions by a factor  $m_e/m_i$ . This difference in energy is the origin of many of the model effects we will now explore.

The success of our mechanism in explaining the observed jet disintegration, as well as other related phenomena, is the existence of anomalous resistivity due to plasma turbulence caused by the jet. This follows because the classical resistivity one obtains when using observed temperatures from the core region all the way out to the radio lobes varies from 1 eV to as much as 1 keV. As a result, classical resistivity is of order  $10^{-16}$  s or smaller, which yields unacceptably long Ohmic diffusion times,  $\tau$ , which would make our model unworkable observationally. However, the fact that jet speeds are of order  $c$  implies that the jet forward electron velocity will have a similar speed, which exceeds by many orders of magnitude either the local ion sound speed,  $c_s = 9.79\sqrt{T_e(\text{eV})}$  km s $^{-1}$ , or the local electron thermal speed,  $v_{T_e} = 4.19 \times 10^2 \sqrt{T_e(\text{eV})}$  km s $^{-1}$ . Thus, once the jet net current velocity begins to grow, it does not have to grow much before it begins satisfying the criteria for the onset of a variety of current-driven anomalous resistivity mechanisms, such as the ion-acoustic and Buneman instabilities [3]. Because of the jet's size, the jet represents a large high inductance circuit which will keep the forward current drift velocity essentially constant on a time scale characterized by plasma processes such as ion-acoustic turbulence. As a result, an excellent approximation often made when dealing with anomalous plasma processes is the 'marginal stability' assumption [4]. This assumption simply states that the driver, here the drift velocity of the net current,  $v_n = V_{\text{threshold}}$ , where  $V_{\text{threshold}}$  is the threshold speed needed to drive unstable a particular mechanism capable of causing anomalous resistivity. To make things simple, we will take  $V_{\text{threshold}} = c_s$  so that the marginal stability assumption becomes  $v_n = c_s$ . This assumption will be used throughout the analysis to follow.

As a result of the electrons having such a disparity in energy relative to the ions, the forward electron current will experience energy and momentum loss with the ambient medium. This energy and momentum loss, principally at the nose of the jet, will manifest itself as Joule heating of the ambient plasma. The physical significance of this effect is that the jet forward electron current will begin to decay away in the Ohmic decay time

$$\tau = \frac{a}{\eta c^2} \quad (1)$$

where  $a$  is the cross-sectional area through which the net current flows,  $\eta$  the effective resistivity is given by

$$\eta = \frac{4\pi\nu_{\text{eff}}}{\omega_{pe}^2}, \quad (2)$$

where  $\omega_{pe}$  is the ambient electron plasma frequency, and  $\nu_{\text{eff}}$  is a generic effective anomalous collision frequency such that  $\nu_{\text{eff}} = \alpha\omega_{pe}$ , with  $\alpha$  typically of the order of  $10^{-3}$  to  $10^{-2}$  [5].

An equation that describes the temporal decay of the integrated forward electron current  $I_F$  is [6]

$$\frac{dI_F}{dt} + \frac{I_F}{\tau} = -\frac{dI_J}{dt}, \quad (3)$$

where  $I_J$  is the bare ion current, i.e. the net ion current that would exist if no electron forward current neutralized the ion current. As  $dI_J/dt = 0$ , because of our original assumption that a jet is the outflow of neutral plasma and not an injection of a charged particle beam, the solution to (3) is trivial, that is,  $I_F = I_J e^{-t/\tau}$ , so the net jet current  $I_n$  grows as

$$I_n = I_j(1 - e^{-t/\tau}), \quad (4)$$

or

$$v_n = v_{j\parallel}(1 - e^{-t/\tau}), \quad (5)$$

where the bare ion current is just

$$I_j = en_{ij}v_{j\parallel}R^2, \quad (6)$$

where  $R$  is the radius of the jet and  $n_{ij}$  is the density.

It is easy to show that if the jet forward electron current were to decay completely away, the resulting magnetic field would be immense. However, before that could occur the jet would begin to disintegrate and thermalize its energy. This can be easily seen as follows. As the self-magnetic field  $B_\theta$  of the jet begins to grow because of the growth of  $I_n$ , the radial particle pressure  $P$  will also increase to balance the rising pinch force of the now partially current neutralized jet. Hence, instead of all the jet particles propagating at the jet speed, they will begin to acquire a large transverse component of momentum so that their gyroradius will increase. Once the gyroradii become of the order of the jet radius, propagation will be inhibited because particles are turned about by their own self-field. This occurs roughly when self-magnetic field pressure equals the plasma pressure, that is, when

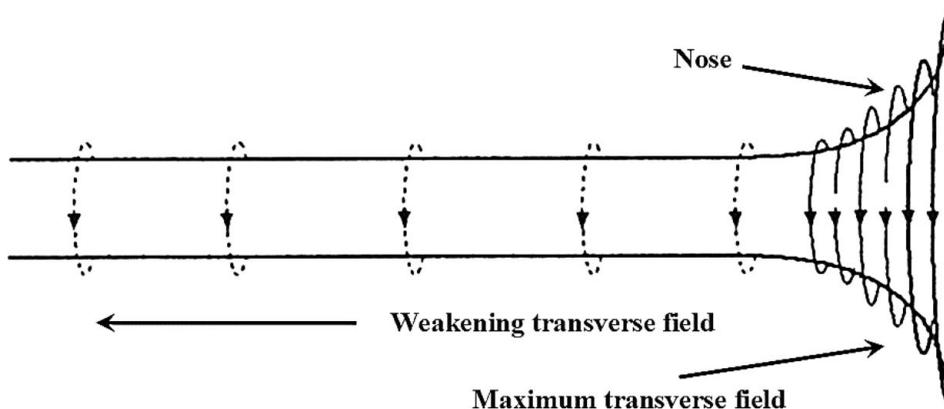
$$P \approx \frac{B_\theta^2}{8\pi}. \quad (7)$$

To estimate when the jet ceases to propagate, a simple model for the radial spatial distribution of the net current is needed. This is easily obtained by noting that because jet ions ‘hole bore’, there will be little interaction between the particles moving within the hole and the ambient particles. Hence, the only region where the electrons carrying the forward current can interact with the ambient plasma is in a thin layer at the outside radius of the jet of thickness  $\delta R = \epsilon R$ . Thus, it follows the area through which the net current flows is roughly  $a \approx 2\pi\delta R R = 2\pi\epsilon R^2$ . Using (5) for small  $t/\tau$ , (1) and the marginal stability condition, one can estimate that jet propagation ceases in a time of order

$$t_c \approx \frac{1}{2}\chi \frac{\epsilon R^2 \omega_{pe}}{\alpha c^2}, \quad (8)$$

where  $\chi = c_s/v_{j\parallel}$ . To determine  $\epsilon$ , we again use the marginal stability condition and use (7) together with  $B_\theta = 2I_n/Rc$  and assume  $P \approx \rho c_s^2$  to obtain

$$\epsilon \approx \sqrt{2} \frac{c}{\omega_{pi}} \frac{1}{R}, \quad (9)$$



**Figure 1.** This schematic illustrates that  $B_\theta$  is a maximum at the nose of the jet and becomes progressively weaker the farther along the jet you go.

where  $\omega_{pi}$  is the ion plasma frequency. In the event there is a pre-existing ambient magnetic field,  $B_z$  along which the jet propagates (9) will need to be altered by allowing  $P \rightarrow P + B_z^2/8\pi$ . If the physics we have discussed is to be relevant to understanding the observed disintegration of jets, then it follows that typical times  $t_c$  must be shorter than the time of flight of a jet from its origin to the point where it appears to begin disintegrating  $\ell$  (usually referred to as a radio lobe). Hence, at a minimum, (8) demands

$$t_c \leq \frac{\ell}{v_{J\parallel}}. \quad (10)$$

We can now recast (8) into a form useful for making estimates. Using the notation  $R = 10^{20} R_{20}$  cm, we rewrite (8) using (9) as

$$t_c \approx 3.0 \times 10^3 \chi \frac{R_{20}}{\alpha} \text{ yr}. \quad (11)$$

As the time of flight  $t_F$  for the jet from its origin to the radio lobe is just

$$t_F \approx \frac{\ell}{v_{j\parallel}}, \quad (12)$$

then using  $\ell = 10^{24} \ell_{24}$  cm, we have

$$t_F \approx 10^6 \ell_{24} \text{ yr}. \quad (13)$$

Equation (13) shows that for reasonable values of  $\chi \approx 10^{-1} - 10^{-2}$  and  $R_{20}$ , the inequality of 10 can be satisfied.

The magnitude of  $B_\theta$  at disintegration is also a useful diagnostic for testing our model. As noted above, jet disintegration will begin when  $B_\theta \approx \sqrt{8\pi P}$  or  $B_\theta \approx \sqrt{8\pi P + B_z^2}$ , if a magnetic field exists along which the jet propagates. Hence, if a magnetic field of this magnitude, which is of order mG for the parameters used, is measured at the nose location, where the jet first begins to disintegrate but becomes increasingly smaller as measurements are made farther back from the jet nose, it would lend support to the model (see Fig. 1). Also, because  $B_\theta$  arises from a thin current layer on the edges of the jet,  $B_\theta$  represents a mechanism for keeping the jet self-collimated. This will be analyzed more in a subsequent paper.

The magnitude of the Joule heat deposited per unit length expected from the decay of the jet electron forward current can be obtained from Spicer and Sudan [6] and is given by

$$W_J \approx I_J^2 \left( \frac{t}{\tau} \right)^2 \frac{\eta}{a}, \quad (14)$$

for  $t \ll \tau$ , which on the insertion of the previously used parameters reduces to

$$W_J \approx 8.6 \times 10^{51} R_{20}^3 \chi^2 \alpha \text{ erg cm}^{-1}. \quad (15)$$

The temperatures expected within radio lobes because of anomalous Joule heating can be estimated again using the assumption of marginal stability. Using the notation  $v_{J\parallel} = 10^{10} v_{J10} \text{ cm s}^{-1}$ , this assumption leads to an electron temperature

$$T_e \approx 1.44 \times 10^5 \chi^2 v_{J10}^2 \text{ keV}, \quad (16)$$

which for values of  $v_{J10} \approx 3$  and  $\chi \approx 10^{-2}$  leads to multi-keV plasmas near the nose of the jet. The enhanced plasma temperatures lead to X-ray radiation at the front of the jet.

As the decay of the jet electron forward current leads to induction electric fields, we also expect non-thermal electrons to be produced at a reasonably copious rate. To estimate the numbers, we note that a rough estimate of the induction electric field  $E_I$  produced is [6]

$$E_I \approx \frac{I_J}{c^2 \tau}, \quad (17)$$

for  $t \ll \tau$ .

### 3. Conclusion

We have shown that there is a natural explanation for the disintegration of an extragalactic jet by the loss of current neutrality in the jet. The regions where disintegration occurs should be accompanied by electron heating and acceleration. In addition, magnetic fields transverse to the jet propagation direction should become finite where disintegration begins and become larger with increasing jet radius.

#### Acknowledgements

Robert Bingham would like to thank the Centre for Fundamental Physics (CfFP) at the Rutherford Appleton Laboratory for support.

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