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DOUBLE LAYERS AND PLASMA-WAVE RESISTIVITY IN EXTRAGALACTIC JETS: CAVITY FORMATION AND RADIO-WAVE EMISSION

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ABSTRACT

For estimated values of the currents carried by extragalactic jets, current-driven electrostatic-wave- and electromagnetic-wave-produced resistivities do not occur. Strong plasma double layers, however, may exist within self-maintained density cavities, the relativistic double-layer-emitted electron, and ion beams driving plasma-wave resistivities in the low- and high-potential plasma adjacent to the double layers. The double-layer-emitted electron beams may also emit polarized radio waves via a collective bremsstrahlung process mediated by electrostatic two-stream instabilities.

I. INTRODUCTION

Extragalactic jets are collimated radio-luminous plasmas that are thought to be supersonic outflows from the nuclei of elliptical galaxies, the jet plasma traveling long distances through the intergalactic medium before being stopped (Begelman et al., 1984). Often, the length of a jet is much larger than the size of its parent galaxy.

The internal plasma pressures of some extragalactic jets are thought to exceed the plasma pressures in the external media. This had led to the hypothesis that these jet plasmas are radially confined via electric-current pinching, the electrical current flowing axially through the column of jet plasmas (Alfvén, 1977, 1978; Benford, 1978), as depicted in Figure 1. The hypothesis that jets carry currents is also supported by electrodynamic models of jet-plasma acceleration (Lovelace, 1976). The presence of currents opens the important possibility that large amounts of energy are being transported down the jets via electrical processes. If electrical currents are in fact present, then electric fields are also expected to be present.

In this report, a model of the electric field that may reside within an extragalactic jet is described. The model involves a plasma double layer or a multiple of plasma double layers in series, each one residing within a density cavity that is created by the action of the double-layer-emitted particle beams.

In section II, the properties of extragalactic jets are reviewed and the Coulomb-collision resistivities and the plasma-wave resistivities within the jets are discussed. In Section III, the double layer model is described. In Section IV, some consequences of the double layer model are discussed, including radio-wave emission from the double-layer-emitted electron beams via a collective bremsstrahlung process, and in Section V, some double layer topics that need further research are pointed out.

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II. COLLISIONAL AND PLASMA-WAVE RESISTIVITIES IN JETS

Subject to great uncertainties, extragalactic jets and the plasmas within them have the following properties (Begelman et al., 1984). The lengths of the jets vary from $L \sim 10^4$ Pc to $L \sim 10^6$ Pc, where 1 Pc $= 3.1 \times 10^{18}$ cm, and the radii of the jets vary from $r \sim 10^2$ Pc close to the galactic centers to $r \sim 10^3$ Pc further out; typical diameters of galaxies are 10^4 to 10^5 Pc. The jet plasma is believed to be of low density, $n \sim 10^{-6} - 10^{-4}$ cm^{-3} and warm $T_e \sim T_i$ 10^5 K, with an additional population of relativistic synchrotron-emitting electrons. The luminosity of the jet plasma is non-uniform, implying higher densities of relativistic electrons and/or stronger magnetic fields in localized hot spots. Estimates of the magnetic field strength yield $B \sim 10^{-5} - 10^{-4}$ gauss. For a few jets that reside in the centers of clusters of galaxies, the ambient plasma is detectable via its x-ray bremsstrahlung, and pressure estimates for these ambient media can be obtained. In some of these instances, the pressures of the jet plasmas are believed to exceed the pressures of the ambient plasmas, and z-pinching of the jets by electrical currents may be acting to confine the jets. Estimates of the total amount of current needed to z-pinch the jets are $I \sim 10^{17}$–10^{18} Amp, implying current densities $j \sim 10^{-23}$–10^{-21} Amp/m^2. If these currents are carried by drifts between the ion and electron distributions, then typical drift velocities are 10^{-5}–10^{-2} cm/s.

These jet plasmas are very nearly collisionless; for a plasma with $n = 10^{-4}$ cm^{-3} and $T = 10^5$ K, the Coulomb-collision conductivity is $\sigma_{\|} \simeq 1.8 \times 10^{13}$ s^{-1}. For a current density $j_{\|} = 1.0 \times 10^{-21}$ Amp m^{-2}, the electric field along the jet required to drive the current is $E_{\|} = 4.9 \times 10^{-7}$ V/cm. For a jet 10^5 Pc in length, this amounts to a total potential drop $\Delta\phi$ of a mere 1.5×10^{-3} V. By almost all standards, the jet is a perfect conductor.

Electrostatic plasma-wave instabilities that are driven by relative drifts between Maxwellian ions and electrons require an electron-ion relative drift velocity v_o that is comparable to v_{te} (Papadopalous, 1977). As mentioned above, the relative drift within an extragalactic jet is typically $v_o \sim 10^{-5}$–10^{-2} cm/s. This drift speed is orders of magnitude lower than the electron thermal velocity. Thus, electrostatic microinstabilities driven by electron-ion relative drifts will not provide electrical resistivities in current-carrying extragalactic jets.

Neither will electromagnetic plasma-wave instabilities that are driven by relative drifts between Maxwellian ions and electrons produce resistivity in extragalactic jets. For a uniform-current-density z-pinched jet in equilibrium, no electromagnetic waves with wavelengths shorter than the jet diameter are unstable (Borovsky, 1986). Hence, no resistivity can be produced.

Note that since anomalous-resistivity processess might not occur in the jet plasma, the jet plasmas might be truely ohmic, at least for the current densities envisioned to z-pinch the jets.

III. THE DOUBLE LAYER MODEL

Some of the properties of strong plasma double layers are as follows (Michelsen and Rasmussen, 1982; Schrittwieser and Eder, 1984). The thicknesses of double layers are $\Delta L \sim 10^1$–10^5 λ^D, the double layers being thicker if the potential jump $\Delta\phi$ across them is greater. The current density within and near the double layer is independent of the local electric field strength; therefore, the plasma containing the double layer is non-ohmic. Ions that drift into the high potential edge of the double layer are accelerated to form a fast, cold beam in the low potential plasma, and electrons that drift into the low potential edge of the double layer are accelerated to form a fast, cold beam in the high potential plasma. The efficiency of turning electrical energy into the kinetic energy of high-energy particles in the double layer is 100 percent. These beams drive space charge waves in the adjacent plasmas (Borovsky and Joyce, 1983), the electron beam drives Langmuir waves and electrostatic electron-cyclotron waves in the high potential plasma, and the ion beam drives ion-acoustic and electrostatic and ion-cyclotron waves in the low potential plasma. If the double layer has a large enough potential drop $\Delta\phi$, then Langmuir waves and electrostatic electron-cyclotron waves will also be driven by the ion beam in the low potential plasma.

Double layers are also characterized by Bohm criteria at their high and low potential edges. For steady-state double layers, these criteria require the ion-inflow drift velocity to exceed C_s and the electron-inflow drift velocity to exceed v_{te}. As was the case for electrostatic plasma-wave instabilities, these required inflow velocities imply large current densities. However, the Bohm criteria may be satisfied without large current densities if a density cavity is formed by the action of the double-layer-emitted beams. When the potential drop $\Delta\phi$ of a double layer is large enough to produce highly relativistic electron beams, the growth length for two-stream electrostatic waves in the high potential plasma is

$$\lambda_{growth}/\lambda_{De} = 2.1 \times 10^{-3} T_e^{4/3}(e\Delta\phi/k_B T) ,$$

and if the potenial jump is large enough to produce a highly relativistic ion beam, then the growth length for high-frequency electrostatic plasma waves in the low potential plasma is

$$\lambda_{growth}/\lambda_{De} = 4.8 \times 10^{-5} T_e^{4/3}(e\Delta\phi/k_B T)$$

(Borovsky, 1986). Because the phase and group velocities of the growing waves are in the direction of the beams, these waves will propagate away from the double layer, leaving regions of calm plasma near the double layer. Beyond these calm regions, however, plasma waves will be present with very large amplitudes (Fig. 2). In the fields of waves on either side of the double layer, the effective collision frequency may approach ω_{pe}. Since the mobilities of charged particles in these regions are small, they require long periods of time to transit to the double layer; accordingly, their number densities are high within these regions. When a particle leaks out of one of these turbulent regions and passes into a calm region near the double layer, it drifts without scattering; this drift being at the thermal velocity, the number density is low (see Fig. 3, top and middle). Thus, the double layer produces electron and ion beams which create two regions of plasma turbulence removed from the double layer itself, these regions acting to keep the plasma density high away from the double layer and creating a cavity around the double layer. It is in this density-cavity region that the Bohm criteria for the double layer can be met; these high drift velocities do not produce high current densities because they occur only in regions where the particle density is low. The current density is conserved throughout the region (Fig. 3, bottom). This cavity production can also be described as the outwardly directed double-layer-emitted beams driving plasma waves that transfer the beam momentum to the ambient plasma, pushing open a cavity and maintaining it with beam pressure.

In order for current to be driven through the regions of electrostatic turbulence near the double layer, resistive electric fields will arise, adding to the potential of the double layer. Note that in this model the anomalous resistivity regions are required, not for their resistive potential drops, but for the reduction of the particle mobility that they cause.

A laboratory example of a double-layer-driven cavity is contained in Figures 9 and 10 of Guyot and Hollenstein (1983), reproduced here as Figure 4. In the first panel of Figure 4, the double layer is clearly visible at $x \simeq 50$ cm. Note also that there is a region of resistive potential drop in the high potential plasma adjacent to the double layer. In the second panel, a density cavity around the double layer is visible. In the bottom panel, the electron drift speed is seen to increase within the cavity. Electrostatic turbulence is detected on both sides of the double layer. Another example of a cavity formed around a laboratory double layer appears in Figure 3 of Sato et al. (1981).

Multiple double layers may occur in a series, each double layer surrounded by regions of beam-driven turbulence that maintains density cavities. The double layers must be separated by distances large enough for their emitted electron and ion beams to thermalize, the thermalized beam particles constituting plasma sources between the double layers.

IV. CONSEQUENCES OF THE MODEL

If they are of relativistic energies, the double-layer-produced beams of electrons will undoubtedly emit synchrotron radiation, making the high potential plasmas near double layers radio luminous. More important, however, the relativistic electron beams will rapidly emit polarized radio waves via a collective-bremsstrahlung process (Kato et al., 1983). The electron-electron two-stream instability that produces the electrostatic waves in the high potential plasma causes the beam electrons to bunch up and the background-plasma electrons to bunch up. The beam electrons are accelerated by random electric fields as they pass through the charge-bunched background plasma, causing them to emit electromagnetic radiation. Because the beam electrons are charge-bunched, they emit coherently. Thus, this emission is like a collective bremsstrahlung, with charge clumps in the beam radiating as they scatter off charge clumps in the background plasma. As observed in the laboratory, the electron beams emit electromagnetic waves with frequencies of approximately $\gamma^2\omega_{pe}$ (Kato et al., 1983), where γ is the relativistic factor of the beam.

It is reasonable to anticipate that a radio hot spot would be associated with a double layer or a series of double layers within a jet, since most of the energy dissipated by the double layer appears as an energetic electron beam that is capable of radiating. Further, if multiple double layers are separated by distances great enough, then the individual radio striations in the jet might be resolvable.

A model that proves to be very similar to this model was developed by Langmuir (1929) to describe the current flows in partially ionized gases. In that model, the inflow of plasma to a double layer was described as an ambipolar diffusion down density gradients. A similar approach may be taken in the present model, with only a change in the nature of the diffusion coefficient.

The double layers envisioned here have many features in common with auroral zone double layers (Shawhan, 1978; Borovsky, 1984). Auroral double layers accelerate electrons to energies of 1–10 keV, the electrons following the terrestrial magnetic field lines to the upper atmosphere where they produce visible auroral arcs. The auroral double layers also accelerate ions upward where they are believed to drive the large-amplitude electrostatic ion-cyclotron waves. The energetic beam electrons are believed to drive Langmuir and electrostatic electron-cyclotron waves, and are also believed to drive collective radio emissions (Anderson, 1983).

V. FUTURE RESEARCH IN DOUBLE LAYERS

There are many topics that must be researched before the double layer model discussed in Sections III and IV is complete.

Two topics important to this model are relativistic double layers and double layers in finite-β plasmas, the stability and dynamics of both types of double layers having yet to be examined. For relativistic double layers, stability factors may favor particular values for the potential jump, such as $e\Delta\phi = m_ec^2$ or $e\Delta\phi = m_ic^2$. For finite-β double layers, beam-driven electromagnetic-wave turbulence may provide another cavity-forming mechanism. Laboratory diagnostics will be difficult to construct for relativistic double layers, and very large plasma chambers will be required to magnetize the particles for finite-β double layer experiments.

Another important topic is the dynamics of multiple double layers. In most laboratory devices, the system potential drops are limited to the ionization potentials of the gases used, and the ions are Coulomb-collisional. To investigate multiple double layers via computer simulation, very large numerical systems must be used to resolve the large-scale phenomena (beam thermalization), the small-scale phenomena (double layers), the fast time scales (Langmuir waves), and the slow time scales (beam evolution). A further goal would be to understand the pre-sheaths at the edges of the double layers. Unfortunately for the theoretical approach, pre-sheaths in collisionless plasmas probably involve electric field fluctuations, and, unfortunately for laboratory experiments, these weak electric field structures are very difficult to observe.

In order to understand the inflow of plasma through the regions of electrostatic turbulence, diffusive flows driven by density gradients and fluctuating electric fields need to be studied.

The spatial evolution of double-layer-emitted electron beams is also a topic for future study. Since these electrons scatter and lose energy as they travel, there will be a spatial dependence of the collective bremsstrahlung spectra. A knowledge of this spectral evolution matched against the spectra of radio hot spots will provide a direct test for the presence of double layer energy dissipation within jets.

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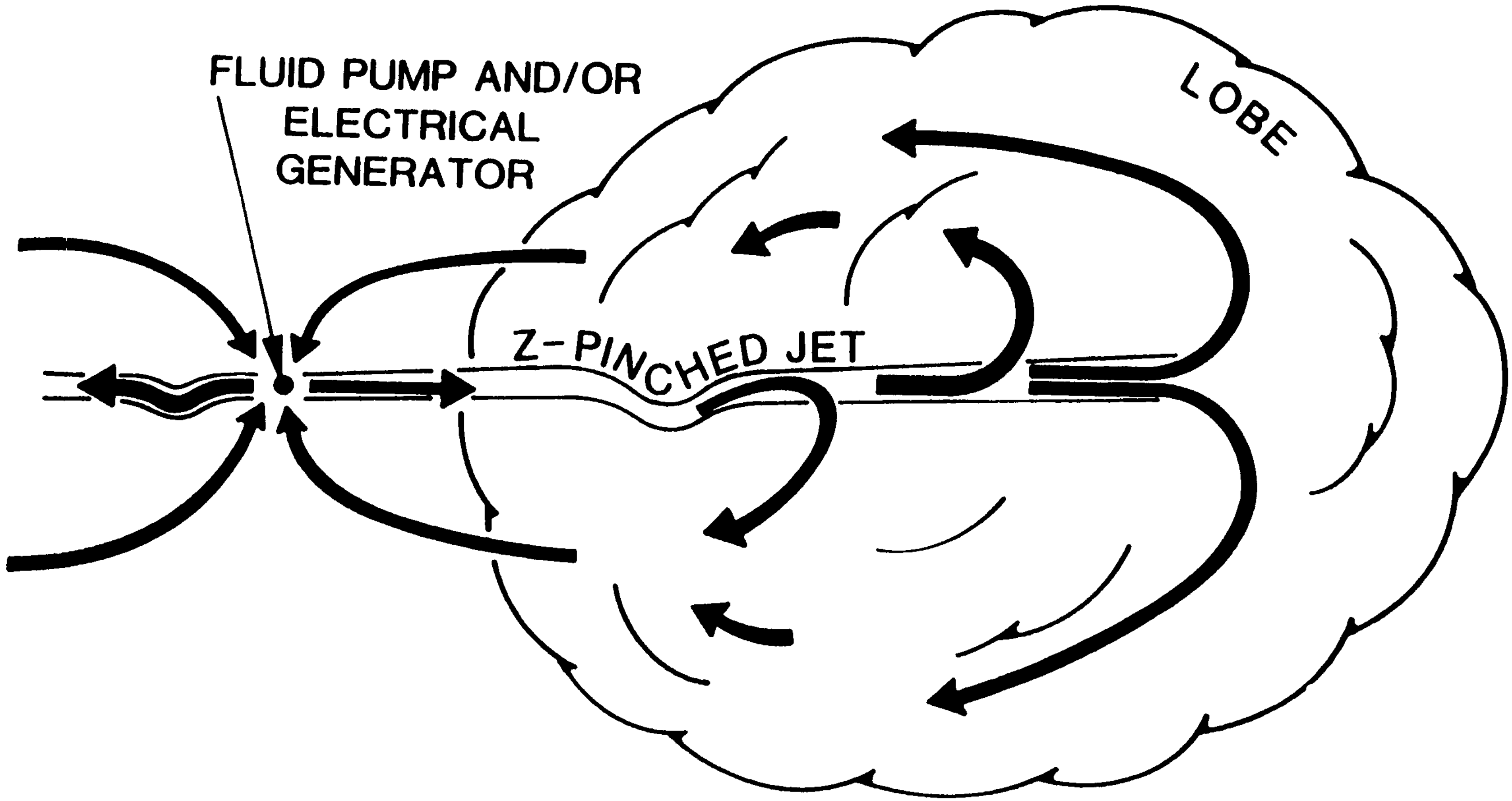

Figure 1. Schematic of an extragalactic jet carrying current within a collimated jet plasma.

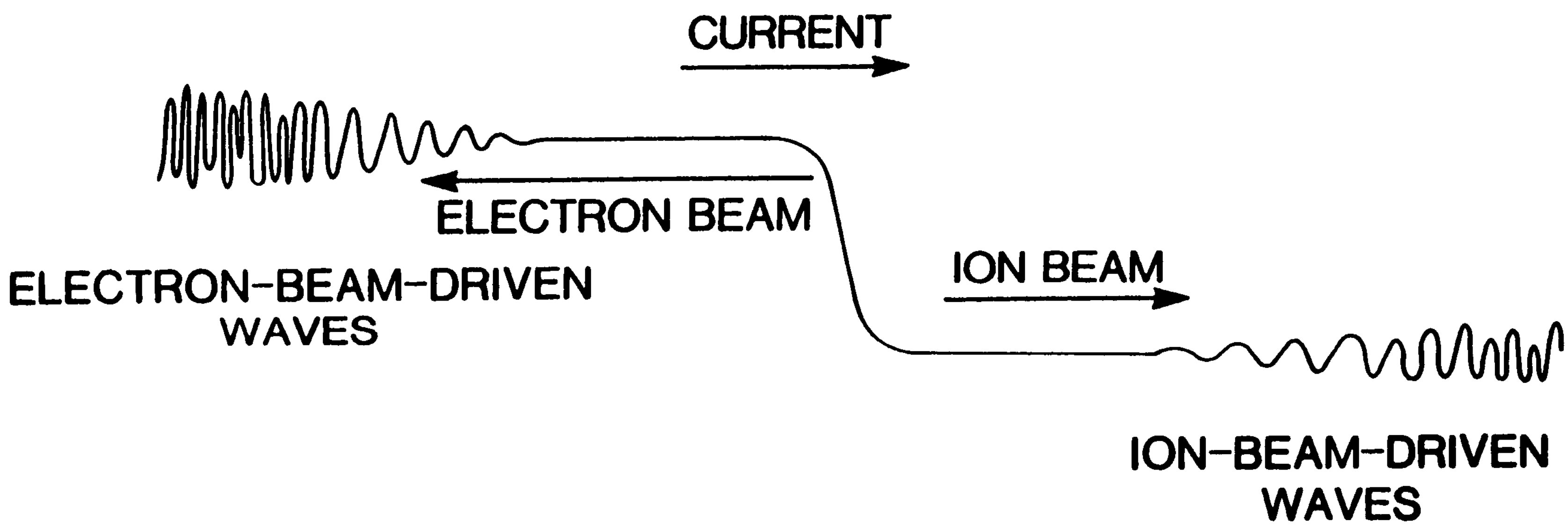

Figure 2. Schematic of a plasma double layer and the waves that the double-layer-emitted electron and ion beams produce.

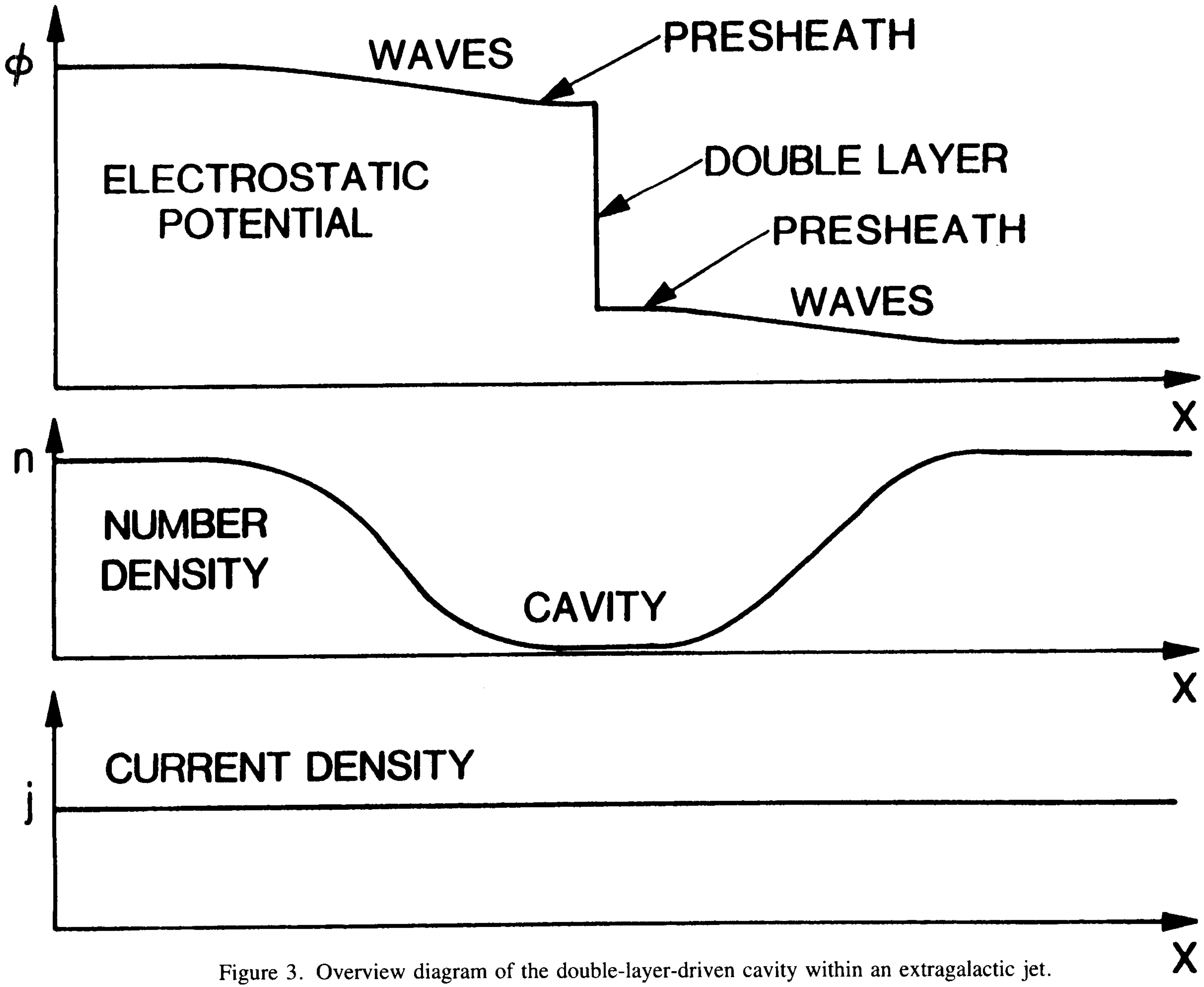

Figure 3. Overview diagram of the double-layer-driven cavity within an extragalactic jet. In the top panel the electrostatic potential is depicted, in the middle panel the particle density is depicted, and in the bottom panel the ,current density is depicted, all as functions of the distance along the jet.

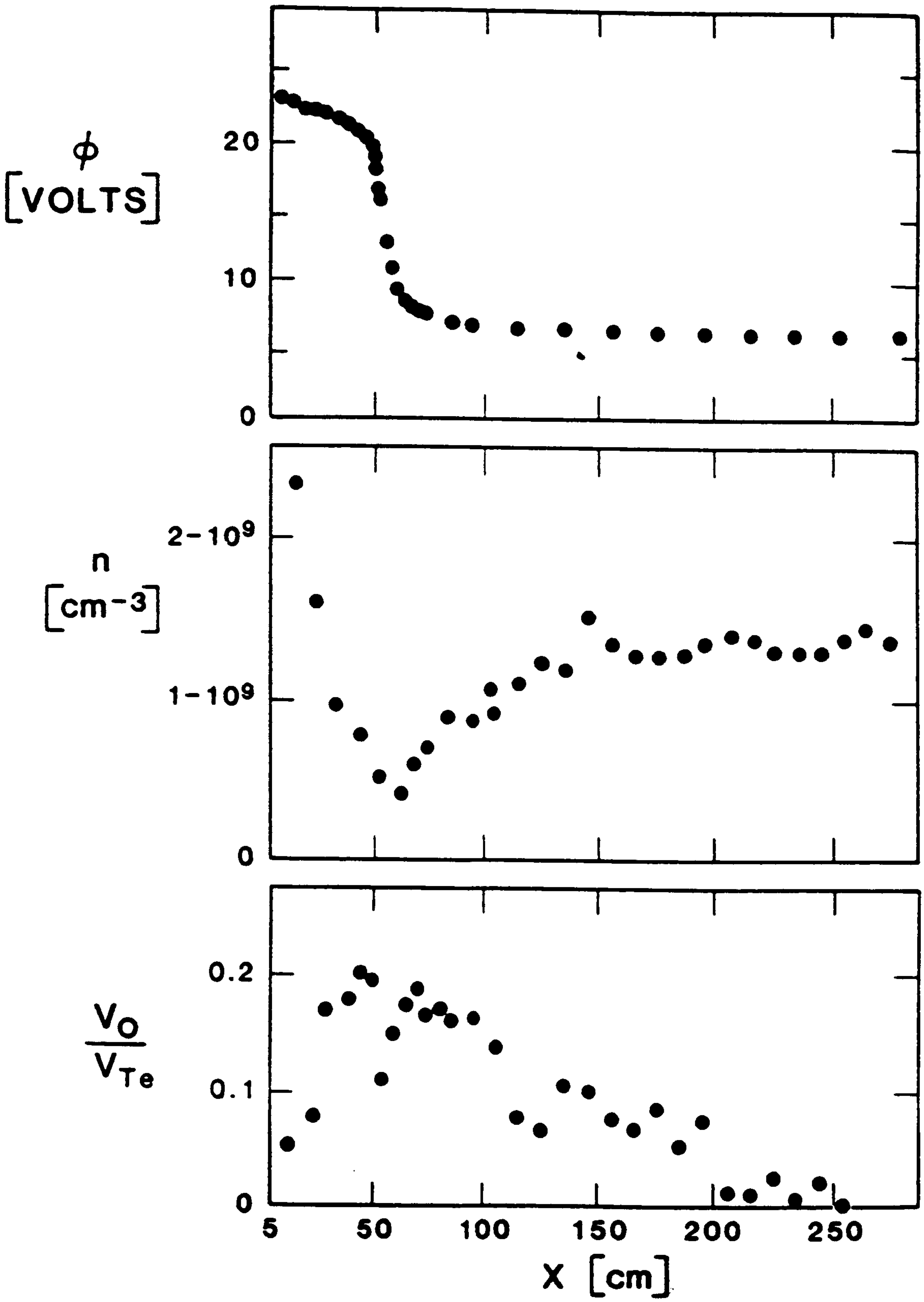

Figure 4. After Figures 9 and 10 of Guyot and Hollenstein (1983), the experimentally measured electrostatic potential ϕ, the number density n, and the electron drift velocity v_o are plotted as functions of distance in the top, middle, and bottom panels, respectively.