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T UAHSPINNING TERRELLA CCELERATOR

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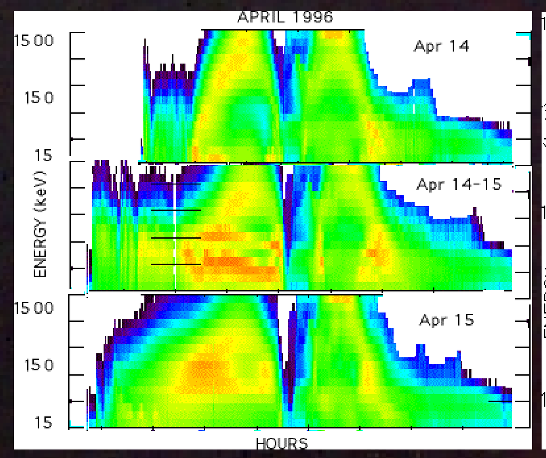
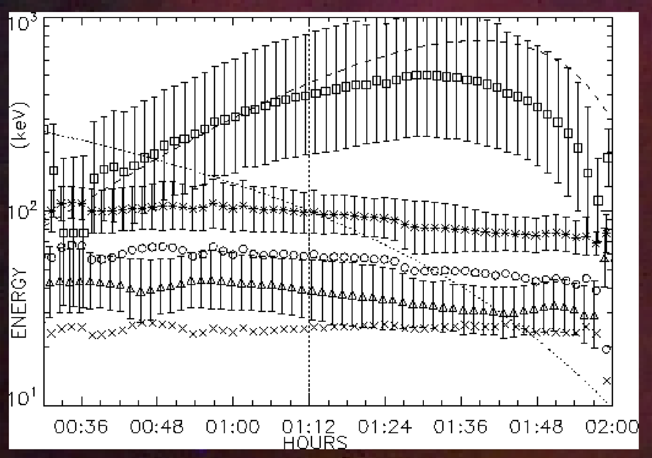
ABSTRACT

The observation of 40 keV ionospheric upflows made with the POLAR/CEPPAD instrument (Sheldon, Spence and Fennell, 1998) has been conjectured as the result of a space-charge driven instability generating kV parallel potentials (Sheldon, 1999), which occur whenever hot plasma drifts in an inhomogeneous magnetic field. Such regions are found at the inner edge of the plasma sheet, where hot plasma is continually injected into the dipolar magnetosphere and grad-B drifts become important, and may accoun t for double layers in the auroral acceleration region. If so, then geomagnetic storms would be an extreme example of this phenomenon since during main phase, the separatrix between corotating and convecting plasma, the Alfven layer, moves Earthward as close as 2.5 Re (Sheldon 1994). This instability provides a simple explanation for duskside Pc1 waves, localized X-rays, ring current filling, Dst enhancements, as well as the O+ enrichment seen during a geomagnetic storm. If this instability, th e Quasi-Neutrality Catastrophe, is a general feature of hot plasma in an inhomogeneous field, then it may also apply at the Jovian Io torus, in solar prominence loops, at accretion disks around youg stars (Herbig-Haro objects), and at accretion disks around black holes (blazars).

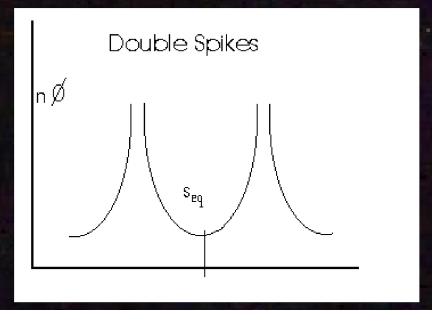
Using simple scaling arguments, we shrink the mechanism down to tabletop size, and propose to measure parallel electric fields in the plasma around a spinning magnet. We report on the results of the UAH Spinning Terrell a Experiment using a Nd-B magnet placed in a refurbished evaporator vacuum chamber, and supplied with a few eV Nitrogen plasma. Previous results at 100 mTorr presented at Fall AGU showed the existence of a hot, 5cm magnetosphere spatially separated from the cooler, ambient plasma injector. We extend those results to lower pressures, DC bias, corotational electric field and plasma composition. By the use of Langmuir probes and crude X-ray detectors, we will present the evidence (or lack thereof) for kV parallel potentials developed in the accelerator. We also emphasize that useable laboratory plasma experiments with important space applications can be built on a tabletop for less than $10,000.

Introduction





The POLAR/CEPPAD observation of 40keV field aligned beams of ionospheric composition simultaneous with convected 90 keV plasmasheet ions () led to the discovery of a kinetic plasma instability we called Sheldon,98 the Quasi-Neutrality Catastrophe (QNC). The instability occurs whenever injected hot ions grad-B drift in an inhomogeneous magnetic field and cannot be neutralized by cold ambient electrons. The idea that disparate ion and electron phase space distributions lead to a parallel electric field date s back at least to Alfven. What we have added is the inevitability of such distributions when hot neutral plasma is injected into the dipolar region of the magnetosphere.



$$\mu\nabla B = -q\nabla\Phi$$

$$\nabla^2\Phi = \frac{q}{4\pi\varepsilon_o}$$

$$qr\alpha\ 1/$$

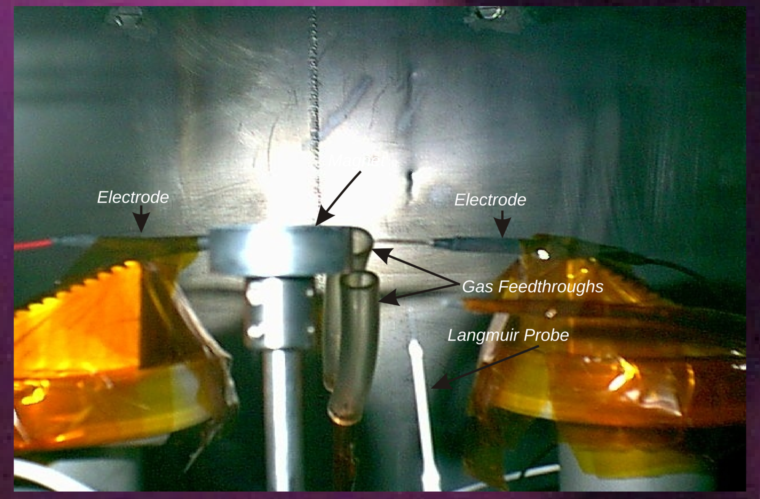
A large space charge builds up that is constrained only by the mirror force, leading to a steep, peaked space-charge potential at the mirror point. Since the magnetic field goes as 1/r, then the grad-B goes as 1/r, and the charge density must go as 1/r. When this steeply rising density integrates to the total amount of injected charge, then the density abruptly goes to zero, and the potential decreases simply as 1/r. Thus the space charge generated potential along a field line has a sharp, double-peaked structure.

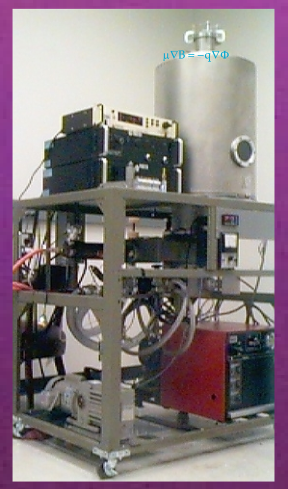
Electrons are accelerated from the ionosphere toward this positive space charge. Their momentum, as well as the "reverse Debye shielding effect" in which an accelerated phase space distribution must in decrease density, cause an "overshoot" of the sharp peak in ions. The addition of a spike and an overshoot lead to a "Mexican hat" potential distribution, with opposing electric fields often called a double layer. This double layer is transient, and would vanish on an electron collision/scattering timesc ale if it were not for the differing grad-B drift speeds of the ions and the electrons that separate the two and begin the process anew. The electrons that have pitch angle scattered in the vicinity of the ions are left behind when the ions grad-B drift away, and find themselves not in the loss cone, but trapped in the magnetosphere. They then produce a second upflowing field-aligned beam of ions. Such ions can be an important ionospheric source of ring current during the main phase of geomagnet ic storms (Sheldon 00).

The large volume of space makes observation of this entire chain of reasoning difficult, however nothing in the theory requires collisionless plasmas or parameter regimes found only in space. Indeed, the entire mechanism can be scaled to fit within a laboratory experiment. This led to the UAH Spinning Terrella Accelerator.

Experimental Setup

For approximately $8000, we converted an evaporator to a plasma discharge system. A Nd-B-Fe magnet was mounted on a stainless rod through a rotating feedthrough to a computer controlled motor. Two high voltage electrodes were mounted on either side of the magnet, each with its own power supply. A Sylvania Cool-White fluorescent tube was used, glass side up, for an X-ray detector. Two Langmuir probes were placed near the equatorial plane of the magnet. An oil roughing pump was used to bring the p ressure down to its minimum value of about 20 mTorr. A needle leak valve was used to establish higher pressures by bleeding in either N2 or He gas. LabView 5.1 was used to control the motor as well as digitize the Langmuir probe data. Several CCD cameras were used to take the pictures, beginning with a Polaroid, a Kodak, both color CCDs with 8-bits of grayscale, and an astronomy cameras, SBIG7T with only B/W but 16 bits of grayscale.

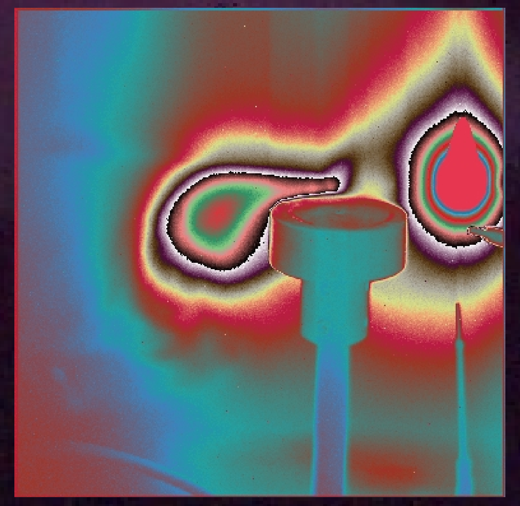


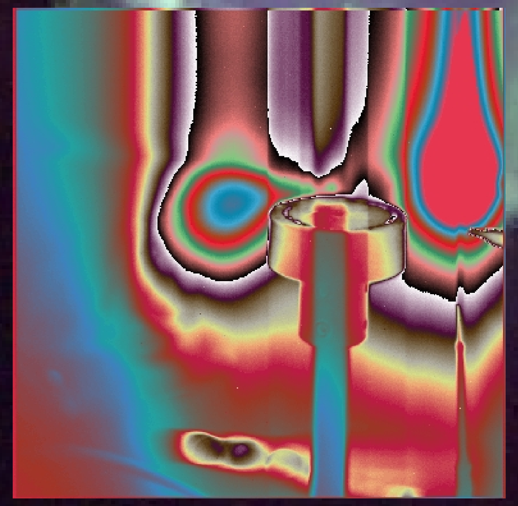


Electron Injection

When a negative potential of about 1 kV is applied to the electrode, a weak purple glow (in N2) indicates that electrons are ionizing the background gas and electrons are injected into the plasma. Electrons that have small pitch angles are attracted to the grounded magnet producing copius X-rays. Faint bluish "horns" can be seen on the field lines that connect the electrode to the magnet. Electrons that have near 90deg pitch angles gradient drift around behind the magnet and can be seen to the left of the magnet as a bluish glow outlining the dipole field lines. The Sylvania X-ray detector brightens as the voltage on the electrode is raised. Electrons that impact on the top of the magnet form a circular aurora made more visible by a light coating of phosphor dust.

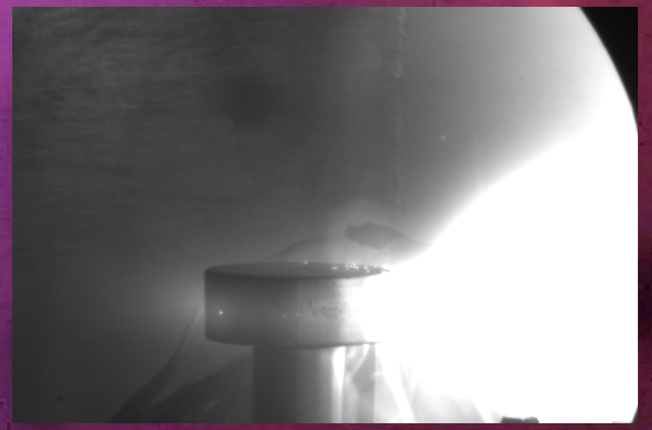
The 16-bit resolution camera was able to better capture the density of electrons as they drifted around the magnet. We show two panels in false color, the left at 2.5kV potential, the right at 4kV. One artifact of the CCD is the "bleeding" upward of the pixels as they are read from the camera. In both panels the electrode was bright enough to saturate the CCD in a small region. Note the auroral zone expands outward as the electron energy is raised. Other than slight density changes, the plasma s how no qualitative differences. Nor did spinning the magnet make much qualitative difference, though it did affect the X-ray shadow.

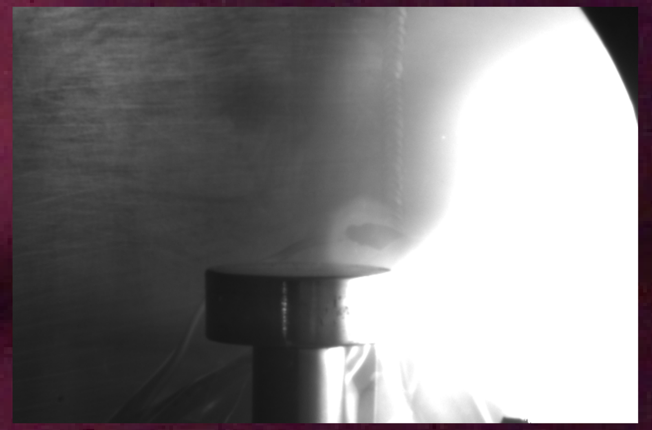




Ion Injection in a Nitrogen Atmosphere

When we applied a positive bias to the electrode, we began injecting ions into the system. As can be seen in the background photograph, ion injection is far brighter because inrushing electrons ionize the gas around the electrode and produce a feedback sheath effect, which in a N2 plasma, is a bright pink corona around the electrode. This feedback meant that a great deal of current was drawn by the power supply, and often only a few hundred volts could be established before the current limit of our power supply tripped. In the following set of pictures with positive bias, we selected a high voltage, usually V>600 Volts, and pulsed the power supply by continuously resetting it. In this way we injected ions of relatively high energy into the magnetic field. The image on the left shows a N2 plasma at 50 mTorr with electrodes pulsed at 600 and 1400 V. The image on the right differs only in being at 300mTorr. Note that at 50mTorr, the ions can drift completely around the magnet, though the large mass of the N+ ion means that ions are trapped only very close to the magnet. So a distinct donut or equatorial distribution can be seen. Occasionally bright spots will flare up around equator, probably due to the potential difference between the plasma torus and grounded magnet causing a feedback ionization or sputtering hot spot. Prominent in the 50mTorr but absent in the 300 mTorr figure are hot spots on the TOP of the magnet (and presumeably, on the bottom as well). These are individua l discharges lasting less than a second that are captured in the 40s exposure. Not as well resolved (due to poor photographic technique) are the thin filaments from these discharges that form complete loops around the magnet. Since the magnet is an equipotential, and the discharge is DC, such a filament can only form if there are parallel potentials along the magnetic field lines. This is expected if the Quasi-Neutrality Catastrophe is occurring!

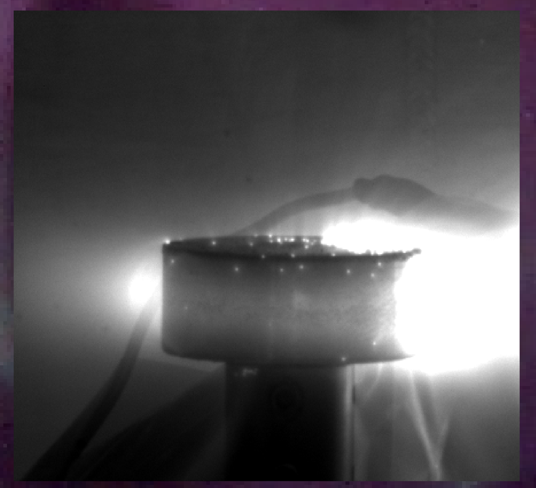


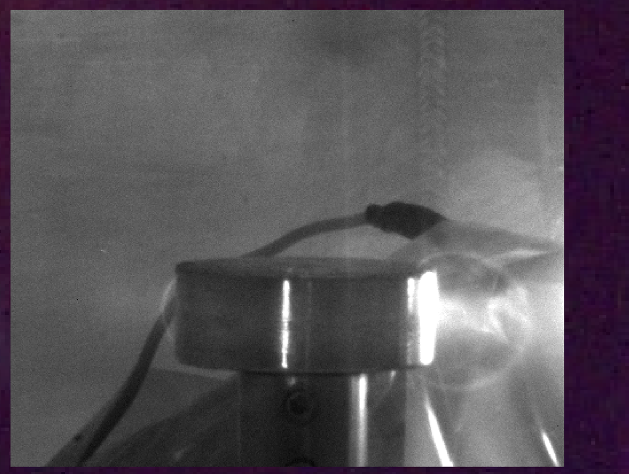


The discharges are more obvious to the naked eye, which seems to have a better transient response. We began to explore the parameters for these circular discharges. Simultaneous injection of electrons did nothing to enhance the effect, and may, in fact, suppress it. Reducing the pressure to 20mTorr also seemed to suppress, or "blur" the circular discharges. Pulsing the positive power supplies at higher voltage also had no effect, nor did spinning the magnet up to approximately 1000 rpm. Since th e trapped plasma appears very close to the magnet, it seems that the gyroradius size is important. We also observed that the initial discharges obtained soon after closing up the vacuum chamber were more intense. We thought the discharge might have something to do with oxygen, and reasoned that a different background gas might show us gyroradius effects. Having a cylinder of Helium handy for the cryopump gave us the opportunity of running a Helium plasma. We switched gasses and obtained the foll owing images.

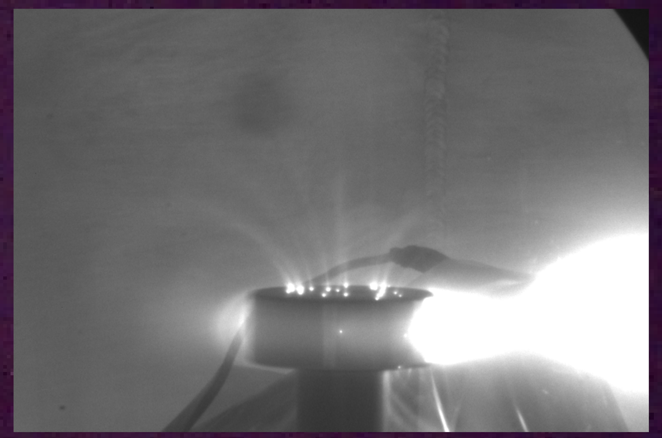
Ion Injection in a Helium Atmosphere

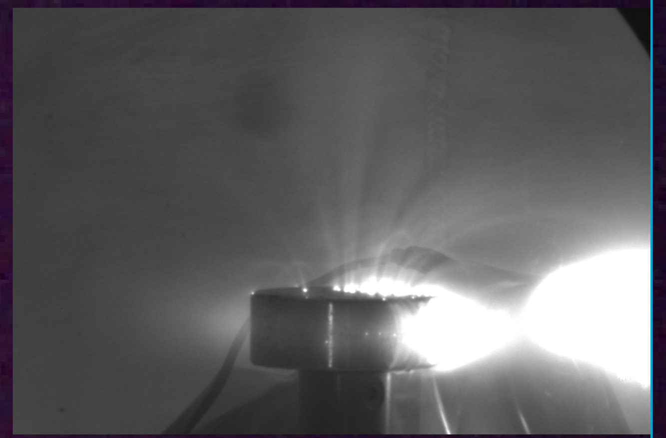
Almost immediately we noticed a great intensification of the circular discharges. The plasma also changed color to a misty white which slowly turned green as the electrodes were sputtered into the plasma. As we raised the pressure of Helium from 60 mTorr to 200 mTorr, the circular lightning became more distinct, and with further pressure increase it reduced in frequency as well as diameter. The left panel is 100 mTorr with electrodes at 900 and 1400 V (briefly). The right panel is identical but at 400 mTorr. Note the many discharges in the left panel, increasing in occurrence on the edge closer to the ion injector. The point discharges along the cylindrical sides of the magnet often occur in pairs, with at least one pair connected by a loop. The discharges from the top can be seen to follow larger magnetic loops. The trapped plasma produces a noticeable bright band at the equator. In the right panel, only two discharges are observed, though comparatively brighter. The larger of the two is closest to the ion injector.





The parameters show that lower pressures are more easily ionized and produce more discharges, while the higher pressures have fewer but brighter discharges. We therefore use 200 mTorr as a good intermediate pressure to show the effect of adjusting the other parameters. In particular, we want to know if spinning the magnet can intensify the process. Note that very little trapped plasma is visible in the higher pressure system, most probably due to the shorter scattering length preventing the ion s from drifting completely around the magnet.



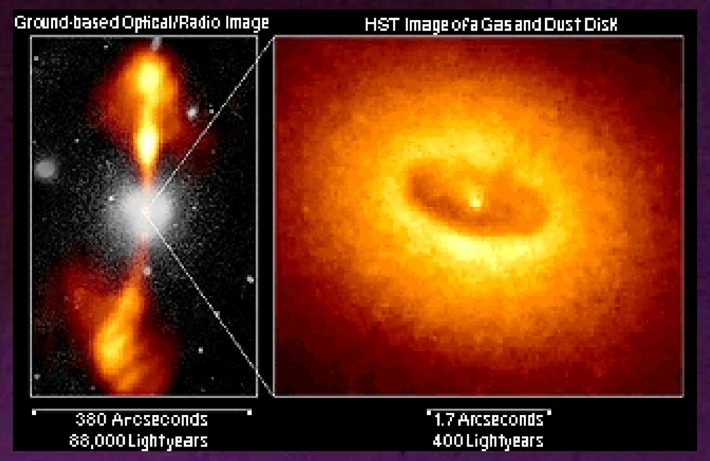


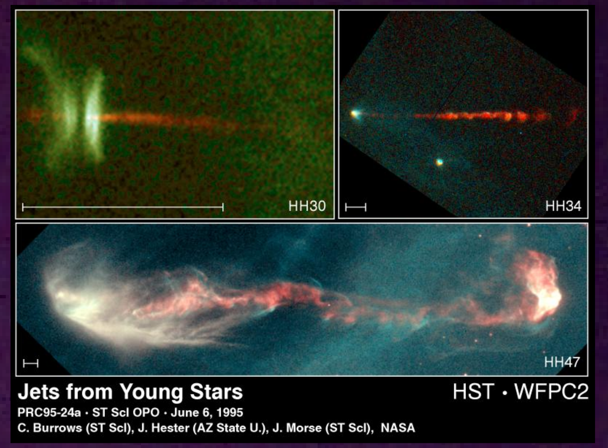
Both panels are taken at 200 mTorr, with 900 and 1400 V on the electrodes. The panel on the left shows the effect of spinning the magnet at approximately 1000 rpm. Note that the discharges are very evenly distributed across the magnet. The torus of trapped plasma appears more intense as well. This demonstrates that even as highly collisional as this plasma is, the induced electric field enhances the separation of charges and produces a more intense trapped ion plasma. Close inspection of the rig ht panel with the stationary magnet reveals an arcade of discharges near the equatorial region at the spot where the advancing cloud of ions grad-B drift away from the magnet.

Discussion

Since 600 V are required to produce a discharge in this density gas, we estimate that approximately half of the 1400 V of the drifting ions is extracted in these discharges, in agreement with the data from space. The robust nature of the discharges, observed over a decade of pressure change, suggest that the phenomenon may be quite common in astrophysical plasmas. At lower densities the discharges occur more readily but are less visible, suggesting that in the rarefied plasma of the magnetosphere, a continuous parallel electric field is generated whenever heated ion injections occur. This may explain the double layers seen in aurora where the ragged inner edge of the plasmasheet injects ions into the dipolar inner magnetosphere. It may also account for the non-adiabatic component of Dst seen in geomagnetic storms when ring current densities exceed that of the plasmasheet (). There are some similarities with solar prominences that may provide fruitful Sheldon 98 examination. But the most compelling analogy is seen in astrophysical jets: young stellar objects (YSO), Herbig-Haro objects, Active Galactic Nuclei (AGN) and microquasars.

Astrophysical Jets





Tastrophysical jets are as beautiful as they are puzzling, resisting interpretation by any comprehensive theory despite 30 years of observations of similarities in their structure. In the panel on the left is a extragalactic jet, while on the right is a galactic jet from a YSO. Microquasars are yet another example of galactic jets recently discovered. All these examples have three characteristics in common in addition to the obvious jet: they have strong magnetic fields, accretion disks and are spinning. As an accretion disk collapses toward the central object (star or black hole) it is heated and ionized, providing a convenient source of hot plasma injected into the inhomogeneous dipolar fields of the central attractor. We believe that the QNC mechanism outlined above can explain the similarities of all these jets. As a check, we note that the parallel electric field is produced by separation of charge in a magnetic field, which first causes a perpendicular electric field. When the p erpendicular field is strong enough, second order drifts (E x B x B) are in the same direction as the electric field and short out the mechanism. Scaling the mechanism described by Rothwell (95) to astrophysical dimensions predicted correctly that AGN's should have a jet energy of ~1 GeV, whereas YSO's should have keV jet speeds. This excellent agreement over many orders of magnitude from laboratory to galactic scales, from centimeters to parsecs, encourages us to believe that we have identified a fundamental length scale for magnetized plasmas. (The next challenge is to describe how a blazar possesses a black hole magnetosphere!)

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