Arrhenius Reconsidered: Astrophysical Jets and the Spread of Spores

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ABSTRACT

In 1871, Lord Kelvin suggested that the fossil record could be an account of bacterial arrivals on comets. In 1903, Svante Arrhenius suggested that spores could be transported on stellar winds without comets. In 1984, Sir Fred Hoyle claimed to see the infrared signature of vast clouds of dried bacteria and diatoms. In 2012, the Polonnaruwa carbonaceous chondrite revealed fossilized diatoms apparently living on a comet. However, Arrhenius' spores were thought to perish in the long transit between stars. Those calculations, however, assume that maximum velocities are limited by solar winds to ∼5 km/s. Herbig-Haro objects and T-Tauri stars, however, are young stars with jets of several 100 km/s that might provide the necessary propulsion. The central engine of bipolar astrophysical jets is not presently understood, but we argue it is a kinetic plasma instability of a charged central magnetic body. We show how to make a bipolar jet in a belljar. The instability is non-linear, and thus very robust to scaling laws that map from microquasars to active galactic nuclei. We scale up to stellar sizes and recalculate the viability/transit-time for spores carried by supersonic jets, to show the viability of the Arrhenius mechanism.

1. INTRODUCTION

The probability of extraterrestrial life has gone through several boom-bust cycles since ancient Greece. At the time of Darwin's publication of "Origin", there was widespread consensus on the existence of life on Mars, on comets, even perhaps on the Sun, as documented by Stephen Dick.[1–3] And widespread life, meant widespread transport, with comets being often cited as the most common means of transport. Darwin's evolutionary theory, however, was incompatible with transport, and within a few decades, scientific support for Darwinism meant denial of extraterrestrial life and transport. It was in this transition that both Lord Kelvin (1871) and Hermann von Helmholtz (1874) independently suggested that comets could easily carry bacteria throughout the solar system and cosmos.

Perhaps hampered by the supposed high temperature of comets (Galileo's fiery messengers), this counter-example to Darwin never got traction. In 1904, Svante Arrhenius calculated that the solar sunlight pressure, ∼1 micro-Pascal at the orbit of the Earth, overpowered the Sun's gravitational attraction for particles <1 micron, or roughly the size of bacterial spores.[4] Therefore bacterial spores released into space from the Earth, could be blown by solar photons out toward Mars, Jupiter and nearby stellar systems. The Arrhenius' mechanism bypassed comets entirely, and given the large number of spores, greatly increased the probability of transport, even if a greater percentage of spores did not survive the transit.[5]

The objections, as might be expected, focussed on the survivability of spores. If, in fact, transport was several orders of magnitude more lethal than Arrhenius assumed, then the his mechanism became less effective than comets. While Arrhenius addressed the dangers of dehydration and UV radiation, he was unaware of cosmic rays. Galactic cosmic rays (GCR), discovered by balloon experiments beginning in 1912, peaked at an energy of about 1 GeV protons and have enough energy to penetrate 5 meters of water, so they are essentially unshieldable for spores and for astronauts. NASA has an outstanding AO for mitigation strategies for human spaceflight, but lacks a flight technology, so missions to Mars must take less than 90 days to reduce the life-threatening GCR exposure. However, bacteria have developed mechanisms for repairing radiation damage, so the question

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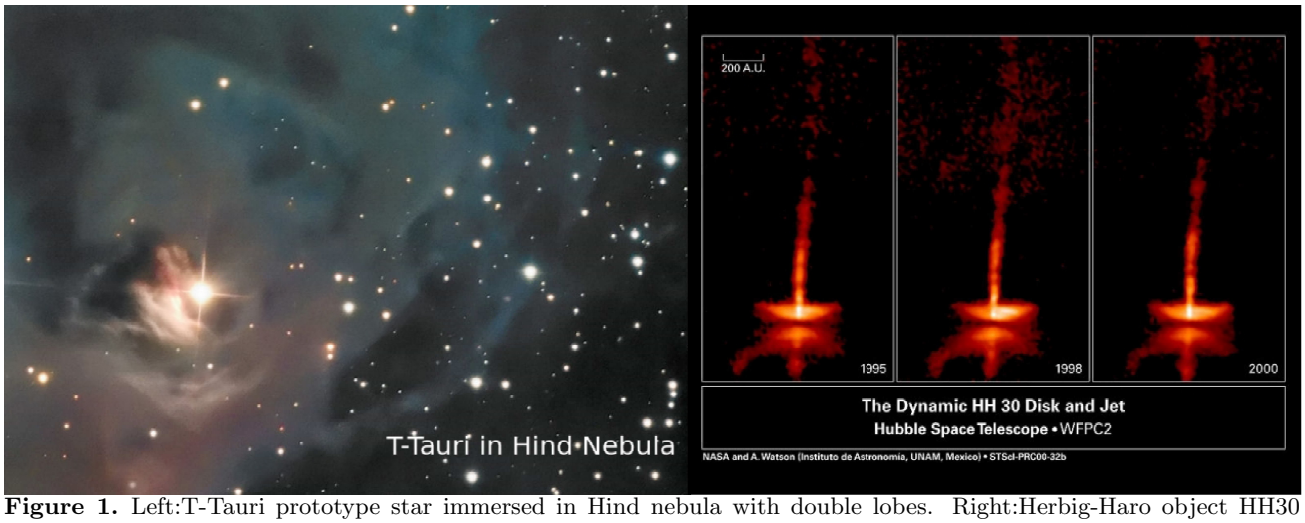

Figure 1. Left:T-Tauri prototype star immersed in Hind nebula with double lobes. Right:Herbig-Haro object HH30 showing jet evolution.

whether spores can survive interstellar transport remains open. We reexamine this problem by considering the possibility that spores can do better than waft from star to star, but can be essentially shot from a cannon.

In section 2, we address the Arrhenius' spore transport problem. In section 3 we address the astrophysical jet observations and the lack of a model of the central engine. In section 4 we develop a theory of astrophysical jets as an electric quadrupolar excited state of a magnetic dipole. In section 5 we design a simple bell-jar experiment to validate the jet theory. In section 6 we analyze the data from this experiment, and show that it reveals a robust, non-linear jet formation. In section 7 we discuss these results as evidence for the mechanism that powers Herbig-Haro jets and entrains bacterial spores. We also contrast these results with that of comets, listing their pros and cons, and then draw conclusions in the final section 8.

2. SPORES

The Gray is a dose unit of ionizing radiation of 1 J/kg. Rad-hardened silicon microchips fail at about 1 MGray, while humans die at doses of about 10Gray. *Deinococcus radiodurans* with multiple copies of its DNA that can repair broken strands, has a 100% survival at 5 kGray and 37% survival at 15 kGray.[6,7] Only slightly less durable is cyanobacterium *Chroococcidiopsis* with 80/8/0.0008/0% survival rates after doses of 2.5/5/15/20 kGray.[8] Unlike *Deinococcus*, however, *Chroococcidiopsis* is a cyanobacterium that can both photosynthesize and fix nitrogen, survive dehydration, freezing and acid environments, making this order uniquely capable of pioneering life in sterile, nutrient-free, pristine environments. The GCR dose at Earth is about 0.3 mGray/day at a peak energy of 1 GeV,[9] which was the same at the Moon behind 4.4cm^2/g of Al shielding (which stops everything below 100MeV).[10] The Sun's magnetic field acts as a voltage barrier to cosmic rays, so outside the heliosphere, it is expected that the rate will rise by a factor 2–4.[11] Using the least favorable rate to estimate a few survivors in a cloud of radiation resistant cyanobacteria we get a maximum residence time of 15,000 Gray/0.0012 Gray/day = 34,224 years in space. If stars are distributed about 4 lightyears apart in our galactic neighborhood, then this gives a minimum velocity of transport of about (4 years$\times 3.14\times 10^7$ sec/year $\times 3\times 10^5$ km/s) / (34,224 years $\times 3.14\times 10^7$ sec/year) = 35 km/s for a few viable bacteria to make it. But if we up the speed to 210 km/s, then 80% of the bacteria can survive the trip.

Are these speeds achievable by spores or dehydrated *Chroococcidiopsis*?

We calculate the acceleration due to sunlight pressure on a sphere of radius r and density D at a distance R from the Sun to be:

$$\begin{aligned} \text{Area} &= \pi r^2 \ \text{ square meters} \qquad (1) \\ \text{Pressure} &= 1/c \times \text{Watts/meter@1AU} = 1360(\mathrm{R_1/R})^2/3\times 10^8 = 4.5\times 10^{-6}(\mathrm{R_1/R})^2 \text{ Pascal} \end{aligned}$$

$$
\begin{aligned}
\text{Volume} &= 4/3\pi r^3 \text{ cubic meters} \\
\text{accel} &= \text{Force/Mass} = \text{Area} \times \text{Pressure}/(\text{Volume} \times \text{Density}) \\
&= (4.5 \times 10^{-6}\pi r^2)(R_1/R)^2/(4/3\pi r^3 D) \\
&= 3.375 \times 10^{-9}(R_1/R)^2/r = a_1(R_1/R)^2/r \text{ m/s}^2
\end{aligned}
$$

Where D is the density of water=1000 kg/m^3, R_1=1AU, and the sunlight pressure drops by the inverse square of the distance. If we equate the gravitational and pressure force, as Arrhenius did to find his maximum radius spore size, we are assuming that the grain is at rest and not orbiting the Sun, otherwise orbital "centripetal" force has already diminished the gravitational force. It is easier to work with the scalar energy than the vector force, so instead we calculate the energy acquired by the accelerated spore and see if it is sufficient to climb out of the Sun's gravitational well from some stable orbit inside such as the Earth. This approach can be generalized to the escape of spores from any of the planets or asteroid belts.

A spore accelerating out of the Sun's gravitational potential gains both gravitational and kinetic energy, so we can equate the work done by sunlight pressure to the kinetic and potential energy gain as:

$$\text{Work} = \int_1^\infty \text{ma}_1(\text{R}_1/\text{R})^2\text{dR/r} = 1/2\text{mv}^2 + \text{GMm/R}_1 \tag{2}$$

where m is the mass of the spore (and cancels out), G is Newton's constant and M is the mass of the Sun. Then the velocity at infinity (escape from the Sun) is:

$$
\begin{aligned}
v &= \sqrt{2\int_1^\infty (a_1(R_1/R)^2 dR/r) - GM/R_1} \text{ m/s} \\
&= 1.414\sqrt{a_1 R_1/r - GM/R_1} \text{ m/s} \\
&= 1.414\sqrt{509/r - 8.82 \times 10^8} \text{ m/s}
\end{aligned} \tag{3}
$$

Using this formula, we can find the largest particle from the Earth that makes it out of the gravity well of the Sun is about 0.57μ radius, but is travelling too slow to make it to α-Centauri alive. The largest spore that has enough speed to survive the trip, 35 km/s, must be <0.34μ in radius. These sizes are perhaps the radius of the smallest cyanobacteria, *Prochlorococcus*, with radii from 0.25-0.4μ, but just barely. Therefore unless we add in some additional acceleration, or raise the starlight pressure, say, by assuming a red giant luminous star, then Arrhenius' original estimate is only marginally possible for specialized cases.

What about Mars? Can it send spores to space more easily? We replace R_1 in the above calculation with $R_2 = 1.524R_1$ and get:

$$v_{Mars} = \sqrt{2(a_1 R_1^2/rR_2 - GM/R_2)} = \sqrt{(2/1.5245)}\sqrt{(509/r - 8.82 \times 10^8)} \text{ m/s} \tag{4}$$

where the weaker pressure and weaker gravitational field at Mars brings out a constant factor, and reduces the maximum survivable radius to 0.28μ, which is marginally incapable of sending cyanobacteria out of the solar system. Conversely, Venus increases the maximum survivable radius to 0.38μ, and finally, Mercury gives a 0.45μ maximum survivable radius. These numbers are just enough to waft the smallest cyanobacteria to α-Centauri, but with huge mortality rates.

On the other hand, there may be other mechanisms that produce acceleration. Solar wind at Earth orbit provides an additional 1 nPa of pressure which is too feeble to be of any help, but T-Tauri stars are thought to lose 10^{-9} solar masses per year in ~100 km/s stellar winds,[12] which comes out to a stellar wind pressure at 1 AU of 22μPa. Since stellar winds diminish as 1/R^2 just like sunlight, we can simply multiply a_1 by a factor 6, which changes our formula to:

$$v_{T-Tauri} = 1.414\sqrt{3034/r - 8.82 \times 10^8} \text{ m/s} \tag{5}$$

Then 2.03 μ radius spores will achieve the minimum speed of 35 km/s. Since this is now well within the range of cyanobacteria sizes, it would seem that T-Tauri stars are quite capable of sending spores to nearby planets.

T-Tauri stars are a subclass of Herbig-Haro objects, all of which exhibit bipolar outflows or jets during their formation from a proto-stellar nebula. Stars about the mass of our Sun are thought to go through a "gentle" T-Tauri stage, whereas larger stars produce higher speed jets during their formation. This is encouraging, because it means nearly every young stellar object (YSO) will produce jets at some time in its development that at a minimum can send spores to nearest neighbors.

But is this jet benign? What if it is generated by γ-ray or α-particle radiation, would that not sterilize any life? We address this question in the next section.

3. JETS

Bipolar jets seem to appear everywhere in astronomy, T-Tauri stars, Herbig-Haro objects, microquasars, X-ray binaries, supernovae, active galactic nuclei (AGN) jets, and even the elusive gamma ray burst (GRB). This diversity spans seven orders of magnitude in length scale, revealing a highly robust generation mechanism.[13] All jets seem to possess a central attractor, an accretion disk, a magnetic field, a collimation that is directly proportional to energy, and long-term stability against beam-plasma and other turbulent modes. Quoting from Smith,[14]

> Astrophysical jets are driven from diverse objects on very different size and mass scales. They can be produced from the vicinity of supermassive black holes in the case of active galactic nuclei (AGN), by star-sized black holes in microquasars, by neutron stars in some X-ray binaries, by protostellar cores in young stellar objects, and by white dwarfs in symbiotic binaries and supersoft X-ray sources. The material of these astrophysical jets is much more than a simple compressible fluid or gas. The gas may consist of a mixture of ions, electrons, molecules and dust particles, or can be dominated by a magnetic field and relativistic particles. The complete quantitative inventory has proved remarkably difficult to establish in all cases.
>
> The truly remarkable fact is that, despite a lack of rigidity, the materials and forces conspire to generate jets with high thrust and power from all these astrophysical objects. The thrust is often sufficient for the jet to excavate a tunnel which transports the gas tremendous distances. For example, jets from the vicinity of supermassive black holes, located deep in the nuclei of galaxies, pierce through the interstellar medium and exit into the extragalactic medium... The same jet is still operating, at least in the same direction, despite ten orders of magnitude (ten powers of ten) expansion.

Yet despite this universality of shape and dynamics, no general scaling law was either derived or sought, instead, a plethora of mechanisms are proposed for each type of object and energy. Current theories put the motor of the jet as a gravitationally driven system extracting angular momentum to form the jet and requiring an external stabilizing magnetic field to shape the jet. But the motor changes with size, with stars driving Herbig-Haro jets, neutron stars powering microquasars, and black holes powering AGN jets. Again, quoting Smith,

> Bringing all astronomical jets under one umbrella is not facilitated by the physics. There are no physical mechanisms or radiation processes to unify a discussion. The flowing material and emitted radiation cover almost every astrophysical possibility. This is because jets stem from a diverse range of objects and are launched through a broad range of environments. The variety is no better demonstrated than by comparing their sizes and speeds, as listed in Table [1]. Their timescales are also simply incomparable.

For if the two main forces are gravity and angular momentum, and the smallest scale size is that of the atoms that make up the gas, then it seems unlikely that turbulence and instabilities could scale eight orders of magnitude from 1 km to 150 Gm (10AU). That is, it is counter-intuitive that gasses driven at higher pressure and energy density should produce larger rather than smaller scale-size structures. Nor is it obvious how the input of a great variety of external magnetic fields should produce such uniform collimated jet output.

So the quotation "not facilitated by the physics" should be seen as a theorist's despair, unable to find a unifying equation. The flip side is that this makes astrophysical jets an experimentalist's playground, gleefully collecting

Table 1. Jet properties (adapted from Smith[14])

Jet type	Source	Supplier	Host	Length	Speed	Time	Size	Dk	#
Cometary	Vent/Fissure	Ice	Comet nucl.	3 Mm	0.1 km/s	10 hrs	1 km	N	>2
Solar spicule	Photosphere	Photosphere	Sun	5 Mm	30 km/s	10 min	100 km	N	>2
Solar coronal	Supergranule	Coronal hole	Sun	200 Mm	200 km/s	10 mins	1 Mm	N	>2
Protostellar	Protostar	Mol. core	Mol. clump	1.0 pc	100 km/s	3 Myrs	$5R_\odot$	Y	2
HerbigHaro	Young star	Gas disk	Mol. cloud	1.0 pc	400 km/s	1 Myrs	$3R_\odot$	Y	2
T Tauri microjet	T Tauri star	Remnant disk	Inter-star cld	0.01 pc	300 km/s	10 yrs	$2R_\odot$	Y	1‖2
Planetary nebula	Post-/AGB	Envelope	Inter-star med.	0.1 pc	300 km/s	300 yrs	$100R_\odot$	N?	2
Symbiotic star	White dwarf	Red giant	Binary	0.01 pc	1 Mm/s	10 yrs	.01 $R_\odot$	Y	2
Supersoft source	White dwarf	Star	Binary	0.01 pc	3 Mm/s	10 yrs	.01 $R_\odot$	Y	2
Cataclysmic var.	White dwarf	Red dwarf	Binary	.001 pc	1 Mm/s	1 yr	.01 $R_\odot$	Y	2
Low-mass XRB	Neutron star	Lo-mass star	Binary	3 pc	0.5c	10 yrs	10 km	Y	2
High-mass XRB	NS/BH	Hi-mass star	Binary	3 pc	0.5c	10 yrs	10 km	Y	2
Microquasar	NS/BH	Star	Binary	0.1 pc	∼1c	0.1 yrs	3 km	Y	1‖2
Pulsar	NS	Pulsar/torus	Supernova	1 pc	0.2c	30 yrs	10 km	Y?	2
Gamma ray burst	Hypernova	Collapsar	Hypernova	0.1 pc	∼1c	100 day	10 km	N?	1?
Blazar/quasar	Massive BH	Galaxy nucl.	Big galaxy	10 pc	∼1c	10 yrs	10 AU	Y	1?
Radio galaxy FRI	Massive BH	Galaxy nucl.	Big galaxy	300 kpc	0.03c	30 Myrs	1 AU	Y	2
Radio galaxy FRII	Massive BH	Galaxy nucl.	Big galaxy	300 kpc	∼1c	1 Myr	10 AU	Y	1‖2

observations, statistics, even lab experiments to quantify the phenomena. In Table 1 we collect information on jets by recreating Smith's three tables but have modified the last column, for when he lists only one jet, this is because observational geometry makes it hard to see the second jet; it does not mean that the second jet does not or cannot exist. We also changed the entry for the pulsar jet from 1 to 2 because the Crab nebula clearly shows two jets,[15,16] and indicated some of the observational uncertainty with question marks.

About the first thing we notice about Table 1, is that the first three items do not have cylindrical symmetry, as can be seen from the last column. The first is not a plasma like all the others, and the second and third do not have magnetic gradient forces like the remainder of the plasmas, they operate inside a nearly homogeneous magnetic field. Indeed, their time scales, spatial scales, composition, and shape are so different that we will summarily exclude the first three items from further consideration. It appears that they were included because Smith used a weak definition of a jet as 'supersonic gas dynamics within slender channels', which continues the astrophysicist's tradition of not distinguishing between a plasma and a gas—two completely different states of matter with very different physics. A gas is incoherent, communicating information from one parcel to another via the sound speed, whereas a plasma is coherent, communicating at light speed. And the principle communication mechanism, the primary driver of coherence, is the magnetic field.

While Smith and numerous laboratory astrophysics experimentalists acknowledge the importance of external magnetic field for collimation of the jet,[17–22] they do not see it as an intrinsic driver, a principle producer of the jet—a job they relegate to gravitational energy and angular momentum. But if plasmas compose the entirety of the observed jets, then neither gravity nor rotational energy contribute as much to the energy density as the magnetic field, and ad hoc externally imposed collimation will necessarily fail to organize the phenomena. We argue that only a fully plasma physics approach can find a unifying principle, and that even a magnetohydrodynamic (MHD) approach is insufficient because this approximation fails in the high magnetic gradient geometries in the central engine of all these jets. And we know these systems have large magnetic gradients just based on the current carried by the jet, but also based on the cylindrical symmetry that tells us that jet system is the same size as the dipole magnetic field. In such systems, the one-fluid approach of MHD is known to fail, so what is needed is at a minimum a two-fluid approach, but most likely a fully kinetic plasma description.

In the next section, we sketch an outline of what a kinetic plasma description of an astrophysical jet might look like.

4. THEORY

4.1. Dipoles

In the absence of monopoles, the simplest magnetic field configuration is that of a dipole. Since higher multipoles fade rapidly with distance, then at the largest scales, all magnetic fields will look dipolar. And all dipoles have two poles, oppositely directed. Therefore the bipolar jets that are nearly universal in Table 1 are easily identified with the two poles of a dipole magnetic field. This identification also maps the accretion disk of these jets onto the magnetic equator of the dipole, which we point out, is precisely where Saturn's rings lie as well. So already we are beginning to see how the underlying magnetic field organizes the jet physics.

We must clear up a potential misunderstanding in the table before we proceed. Black Holes (BH), are observed to have magnetic fields associated with them, but theoretically are denied the opportunity by the "BH have no hair" theorem. Accordingly, astrophysicists have struggled mightily to generate magnetic fields in the accretion disk. We think this is mistaken for several reasons. First, neutron stars are often candidates for the gravitational center of these systems, and they do support magnetic fields. Second, highly magnetized neutron stars may get quite massive—the theory is poorly developed—and supplant BH altogether.[23] And third, and more significantly, BH possess three quantities only—mass, angular momentum, and charge—yet the Kerr-Newman solution of a spinning, charged BH has been neglected in favor of an uncharged, non-spinning 3+1 metric with ad hoc Maxwell stress-tensor added to it, ostensibly without magnetic field. So the reason we have no magnetic fields in our BH models is that the theorists don't know how to put it in self-consistently, which is not the same thing as saying that BH cannot have magnetic fields. Therefore we defer to the observationalists and argue that all astrophysical jet systems have central dipolar magnetic fields that are not due to any disk interactions.

If all these astrophysical jets are magnetic dipoles, then the size scaling is precisely the scaling of their magnetic dipole field strengths. We find a rough equivalence of the jet energy and the magnetic field strength, which we estimate to be about 1-10kV/Tesla.[24,25] Then the earth with its 1 Gauss surface field, or the Sun with its 100 Gauss field can be compared to the 10^8–10^{12} Gauss magnetic fields of neutron stars and magnetars. Clearly if the field can vary over 12 orders of magnitude, then there is a way to achieve the wide range of jet length scales seen in the universe.

So if we place a strong magnetic field into a plasma, the first effect is to organize the plasma into a cylindrically symmetric shape with the plasma impinging on the equator in a ring—the accretion disk—as we discuss next.

4.2. Accretion Disks

At Saturn, and unlike any of the other planets, the rotation axis is aligned with the magnetic axis, which means that electrodynamic effects and gravitational effects do not perturb each other. As a consequence of this cooperation, electric fields form around the equator that compress the charged dust into a thin plane, coupling the plasma to the neutrals. In this three-component system of ions, dust, and ice, the ions provide feedback by sputtering the ice to maintain the plasma that establishes the electric field. But it is the all pervading magnetic field that connects the three and provides a coherent whole.

In a very similar way, gas in the accretion disk is heated and ionized by the accelerated plasma, coupling the accretion disk neutrals to the dipole-trapped plasma. The plasma interacts with the neutrals to change their orbital speed by dynamic friction. The plasma is not Kepler orbiting, but rather E×B drifting around the central attractor, where the electric field under normal conditions of a spinning dipole is directed radially in the plane of the ecliptic. Then the region of highest drift is at the equator, where the angular momentum of the neutral drag on the ions acts as a dynamo for the field, and the field acts as a motor for the ions.

In this region, the ions and the neutrals act as a negative feedback on the electric field. If the field gets too high, the ions speed up and the ion-drag on the neutrals raises the centrifugal barrier to the neutrals, so that they recede from the central attractor, which simultaneously slows them down, and their drag on the ions reduces the electric field. Conversely, if the field diminishes, the ion-drag slows the neutrals, pulling them inward, which by angular momentum conservation speeds the neutrals up so that their drag on the ions increases the electric field.

Plasma ions are made from the neutrals as they are heated and stripped by collisions with the plasma, or by ionizing radiation from the central attractor. In this case, the feedback is weakly positive, with increasing

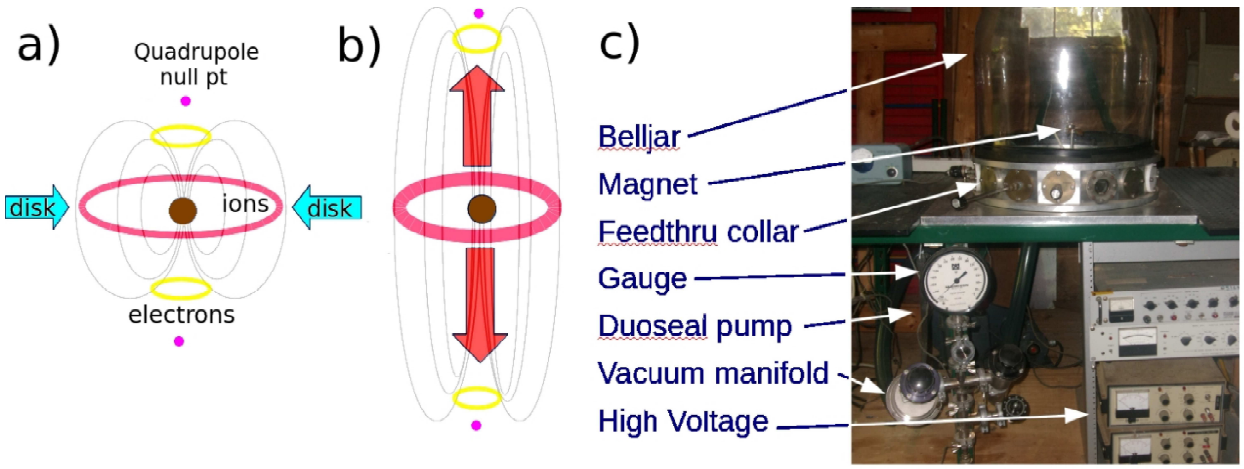

Figure 2. a) Schematic representation of 1st dipole excitation. b) 2nd quadrupole excitation. c) Experiment setup.

plasma densities leading to increasing ionization rates. In this overlap region of the magnetosphere, a mostly neutral outer disk transitions to a mostly plasma inner disk with a strong electric field. So electric field steady state is obtained at a fixed neutral accretion rate, which in terms of energy barriers, is the disk pressure. At higher disk pressures, the electric field is higher and vice versa. The positive feedback of ionization mean that the steady state electric field may be multivalued for the same accretion rate, perhaps in discrete levels of electric field strength depending on the ionization energies of the majority species.

Note that the ion drag causes neutral drag, and the neutral drag propagates outward toward the accretion disk, so that the entire dust cloud begins to rotate in alignment with the magnetic field. So not only does the magnetic field align the plasma, but through collisions it also aligns the neutral dust and gas cloud. In terms of angular momentum, the central attractor transfers angular momentum to the cloud, which upon accretion, convert that back into the plasma which then sets up an equilibrium electric field to referee the interaction and keep it steady state.

This is the stable state of a plasma loaded dipole (see Fig. 2 panel a), until it is driven too hard.

4.3. Ring/Birkeland Currents

The above steady state scenario is an equilibrium that can be computed with one-fluid MHD models. But as the neutrals are ionized, the massive ions remain roughly where the neutrals were concentrated—at the equator—while the more mobile electrons diffuse away. Initially, this ambipolar diffusion of electrons causes a slight positive charge at the equator which in the case of Saturn, attracts the charged dust to a thin equatorial disk, and can be observed in the lab.[26, 27]

The electrons and the ions are spiralling around the magnetic field lines until the field gets too strong and they reverse direction, a motion known as "bouncing". As they bounce up and down the field line, they experience a slower drift motion around the central attractor due to magnetic gradients, that sends the ions in one direction and the electrons in another. Since they carry opposite charge, the current is in the same direction for both, As more and more neutrals are ionized, the equatorial ion plasma becomes a ring current, whose magnetic effect weakens the interior field while strengthening the exterior, so that accretion disk pressure shrinks the plasma as if the dipole was wearing a too-tight belt.

The ions bounce very little as they drift around the equator, but the more mobile electrons bounce far away from the equator. If we define the pitch angle as the angle the charged particle makes with the magnetic field line, then we see that the ions show a trapped, near 90° pitch angle "pancake" distribution, while the electrons have "butterfly" pitch angle distribution peaked away from 90°. The electrons paradoxically find themselves

expelled from the equator because they are accelerated toward the ions and overshoot, spending more time at high latitudes of the dipole near the poles. Thermalizing the electrons would eventually bring them back together, but at high neutral disk pressure, the electrons are continuously squeezed toward the poles where they form two, high latitude ring currents.[28]

It is not that the electrons cannot cross the equator because they are still bouncing, it is just that their residence time at the equator is minimal because of their high speed. So their average location is at high latitudes. This means that their contribution to the ring current occurs in two rings, above and below the equatorial ion current.

So already, the MHD assumption of a single fluid has broken down, because we have ions and electrons separated and forming a polarization electric field aligned with the field. Since the equatorial magnetic field line is principally parallel to the z-axis, the parallel electric field looks like a quadrupole—negative over the poles, positive at the equator. The size of this electric field is proportional to the neutral injection driven by the disk pressure, and can reach voltages proportional to the temperature of the plasma that is adiabatically compressed. At Earth, the ions coming in from the tail (a 1-D version of an accretion disk) reach a temperature of some 100 keV in the inner magnetosphere, while the parallel voltages induced can reach 40 kV under "magnetic storm" conditions when solar "coronal mass ejection" plasma compresses the magnetosphere.[29] Scaling with density and magnetic field, a T-Tauri star has some 1000 times the wind pressure, which would scale up to some 40 MeV voltages in these broadly unfocussed YSO jets.

This sets off additional non-MHD instabilities that compress the electrons and produce a more focussed jet.

4.4. Magnetic Stresses

As more and more plasma carry current, the magnetic dipole field gets distorted. The ring current weakens the interior but strengthens the exterior. The field lines get more "D-shaped" as the current "inflates" the outer regions, with the electrons forming a high-latitude ring current at the two corners of the "D". Then something strange and wonderful happens: the two co-aligned magnetic fields form a quadrupole magnetic field. That is, along the z-axis, the vector magnetic field from the ring current opposes the vector magnetic field of the central magnet but with a slightly longer length scale, so that as we move further from the origin, the magnetic field strength eventually goes through zero strength before going negative. This quadrupole null point is surrounded by higher strength magnetic fields, so that in this region (known as the high-latitude minimum in the magnetosphere), the magnetic gradients reverse.

If with increased neutral injection the high latitude electron ring current reach this region, the drift switches direction and the electron current now is opposite to the ion current, as well as now strengthening the central magnet. Even more bizarre, if some electrons scatter their pitch angles toward 90° in this quadrupolar region, they may never cross the equator again, but bounce around this quadrupolar minimum.[28] This now disconnects the high-latitude current from the equatorial ion current.

But opposing currents repel, so that the electron ring current now moves outward along the z-axis, stretching the field lines into an even more elongated "D" (see Fig. 2 panel b) Or equivalently, because the electron current now strengthens central magnet it moves the quadrupole cusp point further away from the origin. Not only so, but it creates "Helmholz coils" that collimate the interior field lines, the straight stem of the "D-shaped" field lines. Therefore at high enough neutral pressure around the equator of a dipole plasma, the dipole forms a quadrupolar solenoid, whose stretching is proportional to equatorial squeezing.

But in building this picture, we have neglected the effect of separating the charges: the ions at the equator, and the electrons filling the high-latitude rings. This separation of charge creates an electric field, whose energy density is a small fraction of the stressed magnetic field energy (by a factor $1/c$), but large nonetheless.

To summarize, as the we turn up the accretion disk pressure, first the ring current forms, then a quadrupolar magnetic field with two null points, that move apart from each other, storing stress energy in elongated magnetic fields and an increasingly larger electric (quadrupole) capacitor.

Until the capacitor shorts.

4.5. Jet formation

The strong electric fields are formed in the collimated magnetic field region—they are field-aligned electric fields. This field will then accelerate any charged particles that find themselves in this region, and will quickly evacuate it of plasma. It is still possible for neutrals to drift in and become ionized and accelerated, which certainly occurs in the broad disks and weak accelerations of a T-Tauri jet. If this were to occur for bacterial spores, say, drifting in from a dusty accretion disk, then they could be charged up to several 10,000 electric charges and accelerated through 400kV potentials for some 4GeV of total energy, but when divided by the 10^{12} atoms, barely achieves 1 km/s. Far more effective is bombardment of this spore by high speed protons that are also entrained in the jet. Since the spore is travelling with the jet plasma, the relative velocities are low, and we do not expect the protons to ionize or produce radiation damage to the spores.

As an aside, a spore designed for astrophysical jet acceleration would have a tough outer shell to couple to the proton jet, but a relatively hollow interior to reduce its mass and increase its acceleration. This is precisely the characteristics of a diatom silicate shell, which according to Hoyle, has an IR signature present in the Trapezium nebulae.[30–32] Such a shell would also provide protection from low-energy cosmic rays, which are both more abundant and more efficient at ionizing damage.

But what happens when the electric field passes 1MV? At this point, neutral particles are no longer needed to form plasma, but electron-positrons can pair produce out of the vacuum. The electrons would rush back to the center of the magnet to neutralize the ions, but the positrons would accelerate toward the electrons over the poles. Unfortunately, the magnetic field steers them through the center of the electron ring current, so they escape the magnetic quadrupole with most of their energy intact. Outside the electric quadrupole, the field intensity drops rapidly, so the positrons find themselves in two collimated jets leaving the "central engine" behind.

So this model of astrophysical jets predicts that all jets above 1 MV begin as positron jets, though they will interact with surrounding matter and become quite a mixture of subatomic particles depending on energy and density. Below 1 MV, the jets will consist of protons or positive ions that depend on the composition of the surrounding high density disk. Note that as the electric field gets stronger, the stretching of the quadrupole is also greater, so that the higher the energy, the greater the collimation, at least, of the central engine.

These jets are scalable from T-Tauri stars to AGN jets, simply by enlarging the central magnetic field and the accretion disk pressure. The model may even account for GRBs, if the hypernova that preceded the jet were highly magnetized, so that the collapsing star both concentrated (or amplified) the initial magnetic field and provided enormous accretion disk pressure. The takeaway is that magnetic fields are scalable, and the resulting electric fields scale equally well. The physics remains the same no matter what the spatial scale, which would explain why a scaling law found in the laboratory would apparently apply to YSO and AGN jets as well.

In more poetic terms, we might say that the first excited state of a magnetic dipole is an electric dipole (radial electric field), and the second excited state is a magnetic quadrupole and a corresponding electric quadrupole.

4.6. Dynamics

Although our model has been given as a series of dynamic motions initiated by magnetic field, it incorporates a number of non-linear saturation effects that produce stable equilibria. This does not mean the output is steady, however, especially if the driving pressure is time-variable. In particular, radio galaxies seem to obey a bistable state, going from radio loud to radio quiet in just a few minutes of time. Extrapolating this timescale at the speed of light suggest that the central engine of these galaxies is at most 1-10AU wide. If this is the size of a magnetized NS/BH magnetosphere, then we can back out the strength of the magnetic field from our universal scaling law. But more significantly, it tells us that the modulation of the accretion pressure occurs on these timescales, perhaps related to the disruption and "swallowing" of stars in this central region.

Alternatively, the quadrupole "null" point of the jet may itself develop structure, due to trapped populations. We have found that the Earth's quadrupole has a high/low state depending on the presence of trapped plasma in the null point.[33,34] Clearly this sketch of a jet central engine mechanism will require much development. But the best evaluation still remains experiment.

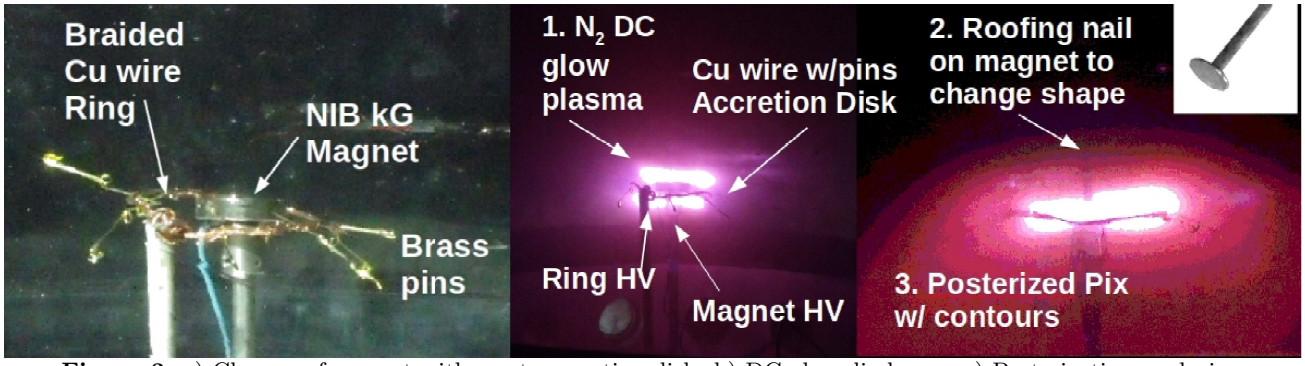

Figure 3. a) Closeup of magnet with ersatz accretion disk. b) DC glow discharge. c) Posterization analysis.

5. EXPERIMENT

We make a weakly ionized magnetosphere by making use of the availability of high strength neodymium-iron-boron (NIB) magnets with surface fields approaching 1 Tesla. Using an oil piston vacuum pump to draw down to the Paschen point, ∼100 mTorr, a relatively low voltage of ∼ -400 V can stimulate breakdown and generate a DC glow discharge. The Ni-plated magnet (mounted on a stainless support rod) emits electrons along dipole field lines that strip nitrogen molecules and form ions confined to the equator of the dipole field. The biassed magnet is electrically nearly equivalent to using a grounded magnet and spinning it to generate the radial electric field, the way the Earth and astrophysical objects obtain their electric field.[25] This discharge generates a characteristic purple glow of excited nitrogen, but now in a donut around the magnet—a magnetosphere in a bottle.[35,36] In this experiment we additionally include a braided Cu ring around the equator of the magnet connected to a separate HV power supply, where we stud the ring with brass pins, so as to insure abundant breakdown plasma (see left panel of Fig. 3).

We photograph the discharge with a 10 Mpixel camera, and then vary the two voltages, the magnet and ring voltage, to find the discharge shape dependence on these quantities. We expected that a high ring voltage will generate more plasma and stimulate an elongation of the discharge. Since we are working in a collisional, weakly-ionized plasma, we do not expect to drive the discharge very deeply into quadrupolar configuration, which requires a large plasma density. So we simulate the quadrupolar state by using a roofing nail placed on the magnet to elongate the magnetic field as the flux lines pass through the high permeability iron. With this elongated magnet configuration we retake the pictures at different voltage discharges.

The high voltages suffered from short-circuiting inside the chamber, as the insulation on the wires was not sufficient to hold more than ∼800 V. Fortunately, the arcs lasted less than the shutter speed of the camera, so that despite staccato discharges, the images show an average glow.

6. DATA

The photographs were analyzed with Gnu imaging software (GIMP), where we posterized the color table from 256 down to 12 levels, which permits us to measure iso-intensity contours easily. The contours are nearly elliptical, so we record the semi-major and semi-minor axes in pixels, or the radial width and the height of all visible contours. Since we are interested only in ratios, we do not convert the pixels into distances (see right panel of Fig. 3).

The contours are line-of-sight brightness contours, which means that even a completely uniform spherical glow would still generate circular contours due to the projection of a sphere onto a plane. We cannot interpret these contours as iso-density contours without deconvolving the projection effect, however, this additional cosine dependence does not affect the ratio of the height to the width, which should be constant for a spherical distribution even with projection effects. Although our contours do not measure equal intervals in plasma density, they do measure a monotonically decreasing plasma density, which is sufficient for our analysis.

Plotting the 8 or 12 values of height versus width for all the contours of one image, we fit them with a linear regression line, generally with a correlation coefficient greater than 0.98, which becomes our "elongation

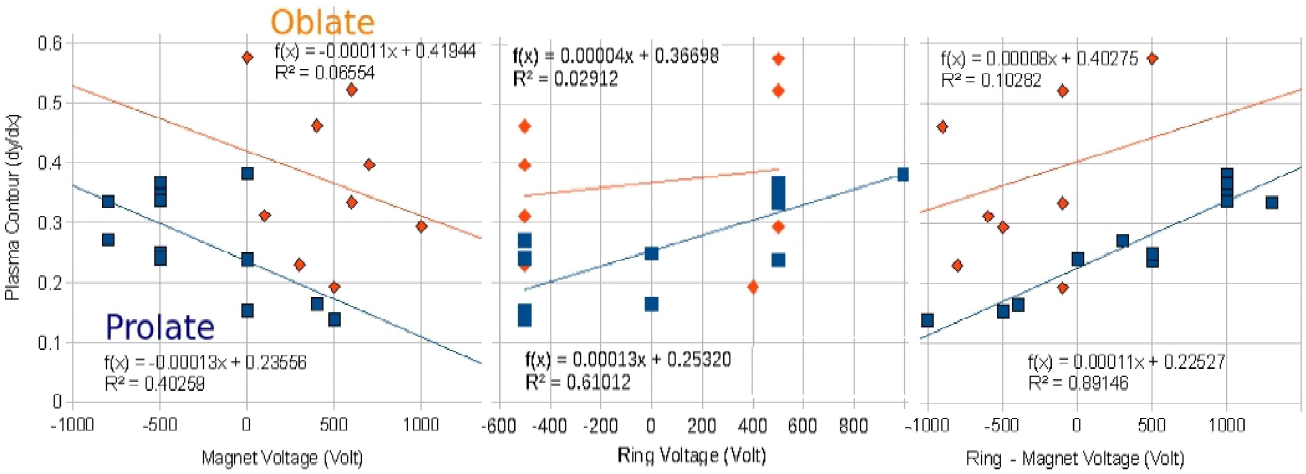

Figure 4. a) Elongation vs Magnet Voltage; b) Elongation vs Ring V; c) Elongation vs Ring-Magnet V.

ratio" for that value of voltages. The high correlation suggests that the iso-intensity contours all have the same ellipticity following the iso-field contours of the magnetic field, up until the last one or two faint contours which show distortions either due to contamination by light or by external magnetic fields.

The elongation ratio is then plotted versus magnet voltage, versus ring voltage, and versus (ring - magnet) voltage (Fig. 4). The data is noisy, due perhaps to the continual arcing of the wires, and has a poor correlation coefficient. The oblate (pancake-shape) magnet showed only weak dependence on any of these voltages, which are not statistically reliable. We attribute this to the non-rigidity of the braided Cu ring, which had vertical distortions or sagging greater than the width of the magnet. When we raise the voltage on this ring, instead of squeezing the dipole field, it is simply distorted. The prolate (elongated) magnet, however, showed much greater response to the ring voltage, though of poor statistical significance until we subtracted the voltages, which is equivalent to measuring an electric field. This last panel shows a dependence of the elongation ratio upon the radial electric field, with a correlation coefficient of 0.89, which given the high noise level, is truly remarkable.

Therefore we conclude that the elongation of the discharge is dependent upon the radial electric field, and is greatly enhanced by starting with a prolate rather than an oblate magnet.

7. DISCUSSION

In hindsight, the highly collisional nature of the DC glow discharge meant that we would never obtain much plasma pressure in our system. At best, the plasma is a tracer of magnetic fields, but it is never a driver. Therefore our goal of mass loading a dipole with injected plasma was doomed to failure. However, the effect of the plasma pressure is replicated by the electric field. So inadvertently we did simulate the pressure driven compression of a dipolar magnetic field using radial electric fields coupling through the plasma.

Now one might counter-argue that the electric fields could distort the plasma with $E \times B$ drifts as well, so perhaps the field lines are not being distorted at all. But if this were true, then the pancake magnet should show the same effects, which it does not. Furthermore, to first order, the radial electric field would cause azimuthal motion of the plasma, not elongation. Therefore we think it more likely that electric field pressure was coupling to the magnetic field, though certainly better experiments at lower pressure would confirm these observations.

Does this experiment validate our theory?

The theory was developed for plasma-pressure dominated magnetospheres, which our experiment does not properly model. But contrary to expectations that collisionless plasmas require huge vacuum tanks to avoid "wall-effects", we show that at sufficiently high magnetic field strength, the dipolar field is quite disconnected from the walls. Indeed, in a collisional plasma, the neutral collision rate disconnects the plasma from everything except the magnetic field. As long as plasma pressure can be simulated with electric fields, then collisional plasmas are easier to form and manipulate than collisionless ones.

The large change in correlation coefficient that depended on the magnet shape shows that the "squeezability" of the dipole field is strongly dependent on its prolate shape. Since the initial excitation of the dipole begins to distort the field, this is a strongly non-linear, coupled feedback system. Thus the jet forms easily, once an initial threshold pressure is passed. Once again, this experimental result shows how robust the jet formation can be.

This is then a first step in testing the theory. We would hope that time on much bigger vacuum tanks with far more sophisticated diagnostics could explore the nature of this quadrupolar excitation. But the simplicity and self-regulated nature of the excitation, as well as the robust scaling observed in nature, suggest that this experiment should be both easy to execute and a nearly unavoidable result of excited dipole fields.

8. CONCLUSIONS

We have updated Arrhenius' mechanism to take into account the depth of the solar gravity well, and the need to achieve high velocity ejection from the gravity well. We include the latest data on the interstellar GCR radiation dose, as well as the radiation resistance of cyanobacteria–the most likely bacteria to colonize extra-solar sterile planets. From this updated model, we estimate that the speeds needed to achieve viable transport require a solar wind pressure of some 20μPa, such as those emitted by T-Tauri stars. T-Tauri stars are examples of astrophysical jets that span the range from 100 km/s stellar jets to lightspeed galactic AGN jets, but a universal theory of jet acceleration is lacking.

We then develop a universal jet acceleration theory involving the quadrupolar excitation of a dipole magnetosphere by equatorial injection of plasma. We apply it to the T-Tauri star and show that direct acceleration is unlikely, but secondary acceleration by entrainment in the molecular jet will accomplish the acceleration. Such entrainment is not expected to radiate and sterilize the spores, and speculate that diatoms are even better designed for acceleration. We then carry out a table-top plasma experiment to show that magnetic dipole magnetospheres do elongate under radial pressure, so the theoretical mechanism has experimental support.

Therefore we conclude that Arrhenius' mechanism still remains valid, even 110 years later.

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