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All the Astrophysical Jet Sources: Driven by Mono-energetic e$^{\pm}$ Beams?

Wolfgang Kundt ⋆

Institut für Astrophysik der Universität, Auf dem Hügel 71, D-53121 Bonn, Germany

Abstract Gopal Krishna and I are now considering $\boldsymbol{E} \times \boldsymbol{B}$-drifting jets since some 25 years, and are still convinced that they form the only consistent description of the huge body of observations. New is our 2004 tightening that (all) the jets consist of mono-energetic flows of extremely relativistic electron-positron pairs, of bulk Lorentz factor $\gamma \lesssim 10^4$, moving in equipartition with their frozen-in magnetic and electric fields. Whenever their supersonic propagation gets blocked by some (heavy) obstacle, their frozen-in Poynting flux converts the delta-shaped particle-energy distribution into an almost white (in power) power law: $E^2 N_E \sim E^{-\epsilon}$ with $\epsilon \gtrsim 0$.

Key words: jet sources — mono-energetic beams — unified scheme

1 SIZES, MORPHOLOGIES, AND SPECTRA

Astrophysical jet sources - or bipolar flows - have been mapped, and studied, since more than 25 years, on scales between outer solar system and several Mpc, with resolutions ranging down below one AU, at frequencies between low radio and hard X-rays, including their various polarizations, and including time-variabilities from hours to decades. At this workshop, Alan Marscher has given a fine overview of the extragalactic class. How are they driven?

The family of jet sources consists of four classes, powered by: (a) newly forming stars, or YSOs - like our Sun, at formation - observed in star-forming regions, (cf. Reipurth & Heathcote 1993, Rodríguez et al. 1998, Reipurth & Bally 2001), (b) forming white dwarfs, inside planetary nebulae (PNe), (cf. Balick & Frank 2002), (c) young binary neutron stars (within light or heavy accretion disks, the latter called BHCs), and (d) the nuclear-burning centers of galactic disks, or AGN, commonly ascribed to supermassive BHs. Classes (a) through (c) are certainly powered by magnetized rotators at their centers, whereas a tenacious myth holds supermassive black holes responsible for the equivalent job in the nuclei of active galaxies, instead of their nuclear-burning centers, ‘burning disks’ (BDs), functioning like 2-dim stars (Kundt 1979, 1990, 1996, 2002, 2004; Kundt & Krishna 2004). Class (a) even contains young brown dwarfs (Whelan et al. 2005). All four classes share the following ten properties:

(i) They drive narrow twin-jets, at right angles to the nuclear disk, of opening angle $\Theta \lesssim 10^{-2}$, which never branch, but often bend, in the shape of the letters U, S, or I (straight, unbent). (ii) The jets are surrounded by cocoons (or lobes), typically of slenderness width/length = 1/5. (iii) They show ‘knots’ (hotspots, Herbig-Haros, FLIERS), and ‘heads’. (iv) They are often ‘sided’, i.e. much brighter on one side of the core than on the opposite side, (v) expand often superluminally, and (vi) have broad spectra, from radio frequencies to X-rays and beyond. (vii) The core/lobe power ratio is $10^{2\pm2}$ (due to strong variability of the core). (viii) (Unscreened) AGN spectra (of nearby BL Lac objects) have been sampled up into the TeV range. (ix) A few resolved ‘nozzles’ of (nearby, supersonic) jets had diameters of $\{10^{14}, 10^{16}\}$ cm for the {stellar, galactic} case, respectively. (x) The sources come in two different morphologies, of Eilek (et al. 2002) type A or B, (refining the much earlier Fanaroff & Riley classes II and I), depending on whether or not their head ploughs supersonically into its ambient medium; in the first case, the terminal hotspot (head) is at the outer edge.

⋆ E-mail: wkundt@astro.uni-bonn.de

In principle, the listed ten properties of the jet sources can be realized by 'hard' or 'soft' beams, i.e. by density contrasts $\Omega := \rho_{\rm jet}/\rho_{\rm amb} = 6kT/m_{\rm p}c^2 \gg or \ll 1$ inside/outside of the jets, whose working mechanisms correspond to those of a lawn sprinkler, or hair drier, respectively. But in particular the sidedness (iv), the superluminal appearance (v), the hard (relativistic) spectra (vi), and the stable, confined morphologies (i) argue in favour of a relativistically light beam substance, $\Omega \ll 1$, whose electrons propagate almost at the speed-of-light, and radiate exclusively in forward direction. Charge neutrality wants electrons and positrons at equal numbers, as protons would upset the dynamics (by their 1836 times higher inertia), and would require an efficient ('in situ') transfer mechanism of their energy to the (radiating) leptons. That leaves us with relativistic pair plasma in supersonic motion, as the only viable beam composition (Kundt 1979, 2004; Kundt & Krishna 1980).

The Lorentz factors γ of synchrotron radiation by relativistic electrons, of frequency $\nu_{\rm S}$, obey

$$\nu_{\rm S} \ = \ 10^{14.6} \ {\rm Hz} \ (\gamma^2 B_\perp)_8 \ , \tag{1}$$

where $B_\perp$ is the transverse magnetic field strength (measured in Gauss); optical frequencies are therefore emitted for $\gamma^2 B_\perp = 10^8$G, and X-rays for at least 10^3-times this value, e.g. for a transverse B of order mG, and $\gamma = 10^7$. Correspondingly, inverse Compton radiation at frequency $\nu_{\rm C}$ obeys

$$\nu_{\rm C} \ = \ 10^{26} \ {\rm Hz} \ \gamma_6^2 \nu_{14} \ , \tag{2}$$

i.e. yields TeV-energy photons by upscattering optical photons ($\nu = 10^{14.6}$ Hz) with Lorentz factors $\gamma \gtrsim 10^6$. Both mechanisms are probably at work in the jet sources. Electrons (and positrons) of such high Lorentz factors can still be transported almost lossfree in the beams through significant (cluster) distances if their motion is an $\boldsymbol{E} \times \boldsymbol{B}$-drift, i.e. a propagation at right angles w.r.t. toroidal B-fields and radial Hall fields (of almost equal strength), the only 'degradation' being inverse-Compton losses on the photon background; the latter obey (Kundt 2004):

$$ct_{\rm deg} \ = \ \gamma/\gamma' \ = \ {\rm Mpc} \ /\gamma_6 \ (1+z)^4 \ . \tag{3}$$

In the next section I shall argue that the bulk Lorentz factors in all the jet sources are (uniform and) much smaller than inserted above, $\gamma \lesssim 10^4$, so that their radiative losses are tiny (during propagation through vacuum channels), consistent with their observed hard spectra all the way out to the distant heads.

In this section, I have described the characteristic appearance of all the cosmic jet sources, and repeated my earlier conclusion that their (ten) properties can be modeled by extremely relativistic pair plasma $\boldsymbol{E}\times\boldsymbol{B}$-drifting through self-rammed vacuum channels. As a final equation of this section, I still want to estimate their bulk Lorentz factor from their occasional (transverse, seemingly) superluminal motion (v), at small angles w.r.t. the line-of-sight. Special-relativistic kinematics yield:

$$\beta_\perp \ = \ \beta \sin\Theta \ / \ (1 - \beta\cos\Theta) \ \leq \ \{\beta\gamma \, , {\rm cotg} \ \Theta\} \ , \tag{4}$$

implying $\gamma > 40$ for observed $\beta_\perp \lesssim 40$, because realistic angles Θ of observed core jets w.r.t. the line-of-sight cannot be expected to be better defined than within one deg, say, and the exact formula can only yield inequalities for γ, not well defined numbers, consistent with $\gamma = \infty$.

2 MONO-ENERGETIC BEAMS

How exactly does the relativistic pair plasma move through its self-rammed vacuum channels? Where and how are the observed broad power-law populations of electrons and positrons generated? Why are their spectra still hard at their outer extremes, after millions of years of propagation? These questions were left open in my 1980 Letter with Gopal Krishna, yet answered in our update in 2004.

The insight came through a close look at Maxwell's equations, combined with the relativistic equation of motion of the electrons (and positrons; omitting Dirac's radiation-reaction term):

$$c \ d(\gamma\boldsymbol{\beta})/dt \ = \ (e/m_{\rm e})(\boldsymbol{E} \ + \ \boldsymbol{\beta} \ \times \boldsymbol{B}) \ . \tag{5}$$

Via Fourier expansion, it is possible to write down the general (axi-symmetric) solution for charges of both signs moving unaccelerated through a cylindrical tube, at arbitrary speed, with net current zero. They convect toroidal magnetic fields B, and radial (electric) Hall fields, of almost equal strength so that the force term on the RHS vanishes (for $\beta \approx 1, \gamma \gg 1$). Such comoving electromagnetic fields - at equipartition of energy, or pressure, with the particles - have been routinely inferred from the radiated intensities and polarization, and are expected as remnant fields from the high-field regions of pair creation (via recombination). Their electric potential Φ is gigantic:

$$e\Phi \ = \ e(\pi \, L \, / \, c)^{1/2} \ = \ 10^{19.5} eV \, L_{44}^{1/2} \ . \tag{6}$$

As soon as such an $\boldsymbol{E} \times \boldsymbol{B}$-drift is arrested, by some (heavy) obstacle, the electric field re-accelerates the convected charges to both larger and smaller energies, by a single fall through the potential Φ, into a broad power law, and gives rise to the luminous appearances (of the knots, and heads). Note that this 'in situ' acceleration involves no multiple-step stochastic upscattering – in likely conflict with the second law – which has been widely postulated in the literature.

So what is the expected energy distribution of the charges during their $\boldsymbol{E} \times \boldsymbol{B}$-drift, along their conical channels (which have been approximated by cylinders in our 2004 presentation, for simplicity of the formulae)? A close look at the equation of motion shows that this transport requires mono-energeticity: Charges of deviating energy are moved radially inward or outward, and thereby re-accelerated, such that they adjust to a uniform Lorentz factor throughout the whole cross section, independently of their sign of charge, to within ten significant figures and more.

It may sound strange that nature could set up focussed, mono-energetic relativistic flows, abundantly so, in non-biological systems. But allow me to sketch the steps along which Krishna & I (2004) have arrived at this conclusion. First of all, the central engine (CE) must be able to generate (relativistic) pair plasma, abundantly so. The only viable mechanism I can see is magnetic reconnections, inside the strong and rapidly varying inner magnetospheres of the CEs; all four above classes qualify, for (large enough) voltages $B\Delta x \gtrsim 10^6$ G cm.

The newly created charges, electrons and positrons, will try to escape from their deep central potential wells, via buoyancy. In this process, they are post-accelerated by the outgoing strong low-frequency magnetic-dipole waves, of strength parameter $f := eB/m_{\rm e}c\omega = 10^{14.2} B_3/\omega_{-4}$, to maximal Lorentz factors of order $f^{2/3} = 10^{9.5}(B_3/\omega_{-4})^{2/3}$, like in the pulsar windzones. At the same time, they suffer inverse-Compton losses on the thermal photon pool, in proportion to γ^2, and are thereby cooled, like atomic beams in the lab when crossing laser beams, with asymptotic Lorentz factors $\gamma \lesssim 10^4$. Their energy distribution will thereby approach a relativistic Maxwellian.

The quasi-radial escape of the relativistic pairs from the CE's post-accelerating windzone - seen as the broad-line-region of an AGN - will be opposed by the ambient (thermal, hence heavy) CSM, and will eventually funnel the pairs plus their frozen-in fields into coaxial escape channels, in the shape of (two opposite) deLaval nozzles, beyond which their supersonic $\boldsymbol{E} \times \boldsymbol{B}$-drift takes over, and narrows the Maxwellian distribution into one of delta-function shape. Note that the corresponding generation of mono-energetic relativistic electron beams has been recently achieved in the lab (Katsouleas 2004).

It remains to discuss the fate of such thin, relativistic beams during their thrust through the CSM, or CGM of their CE. Clearly, their inertia is $\Omega = 6kT/m_{\rm p}c^2 = 10^{-8.3} T_4$ times lighter than that of their (baryonic, at temperature T) surroundings, hence they move like confined by concrete walls, with no splitting ever, guided by their comoving fields. If tapped near their periphery by surface roughness, their spectra can be mono-energetic, whereas sizeable obstacles (in the hotspots) tap their comoving potential, and establish power-law spectra, as estimated by the relativistic Child's law (for a space-charge limited flow). Details of this terminal re-acceleration (in a knot, or head) must be complicated, whereby a beam is slowed down by an obstructing (heavy) conductor via a compression of its magnetic field, and of its (low) convected excess-charge density (of both signs) such that the force-free $\boldsymbol{E} \times \boldsymbol{B}$-drift of the beam plasma is transformed into gyrations around $\boldsymbol{B}$ together with radial drifts, which continue filling up the cocoon (with more-or-less reflected, subsonic, extremely relativistic pair plasma).

The matter-antimatter beams described in this talk are not totally new. They were already considered by Phil Morrison in his 1981 evening lecture at Socorro, and taken seriously by Fukue (1986), Reipurth & Heathcote (1993), Scheuer (1996), Prieto et al. (2002), Brunetti (2002), and Stawarz (2003), though hardly by Begelman et al. (1994). A direct test of their realization in nature – via the 511 keV pair-annihilation line – is unexpected at the present sensitivity of γ-ray telescopes because of the low density of the positrons both in the jets, and in their lobes, and because of the low annihilation cross section of relativistic pairs; only after thermalization, in interaction with the boundary-layer material, do cross sections grow large enough.

Still, Kaiser & Hannikainen (2002) have highlighted redshifted 511 keV radiation from eight Galactic X-ray binaries with jets. And the recent *INTEGRAL* map of the sky at 511 keV shows the Milky Way as an emitter, at a rate of $10^{43.3}$ s^{-1}, of which some 83% come from the bulge, $r \lesssim 2$ kpc (Knödlseder et al 2005). The authors talk of decaying ^{26}Al and ^{44}Ti as likely emitters, ignoring the fact that the whole stellar bulge would have to be processed and annihilated through this channel. I prefer a spillover interpretation via all the Galactic jet sources (Kundt 1997), dominated by the (variable) VHE source Sgr A* at our Galactic center (Aharonian et al 2004).

3 CONCLUSIONS

The (four classes of) astrophysical jet sources are interpreted as driven by extremely relativistic pair plasma, of bulk Lorentz factor $\gamma \lesssim 10^4$, coasting mono-energetically through self-rammed vacuum channels in the form of a loss-poor $\boldsymbol{E}\times\boldsymbol{B}$-drift. The pair plasma is generated in the recombining magnetic fields of the (distorted) inner magnetosphere of the central magnetized rotator, post-accelerated by its low-frequency waves, cooled by its photon bath, and ultra-cooled by its convected Poynting flux. The pair plasma's spillover annihilation radiation in our Galaxy has been recently mapped by *INTEGRAL*. By a similar mechanism, mono-energetic electron beams have been recently produced in the lab.

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