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# HIGH-ENERGY DENSITY JETS GENERATED BY LASER FACILITIES IN LABORATORY ASTROPHYSICS: EXPERIMENTS AND SELF-SIMILAR EVOLUTION

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**Abstract.** Recently, we performed laboratory jet experiments using the LULI2000 facility. We tried to characterize completely the generated jets and study their similarity properties. Moreover, we performed analytical work in order to understand experimental results. We tried to find self-similar solutions with the Burgan-Feix transformation that we will present in this paper.

## 1 Introduction

Astrophysical jets are one of the most fascinating astronomical objects ever observed. Many observations show that jets powered by young stars (Bally et al. 2002) possess a knotty but coherent structure on very large distances. These jets constitute a fundamental information about the accretion history of the young star. Our comprehension of jet properties is still partial and laboratory astrophysics (Remington et al. 2006) seems to be a very promising way to study them. Reproducing and mastering radiative jets equivalent to an astrophysical situation (with the good scaling laws) in laboratory is a challenge. Understanding radiative losing effects on the dynamics and the structure of the jet is possible using laser facilities. Several studies have been performed with intense lasers: radiative collimation (Shigemori et al. 2000) into vacuum and interaction between jets and solid (Foster et al. 2005). Recently, we made jet experiments using the LULI2000 facility (Koenig et al. 2007), (Loupias et al. 2007). In our experiments, we used a new flexible target which allows to introduce easily an external medium. We studied the best configuration in order to obtain the most collimated jets. For every shots, we characterized created plasma jets. Furthermore, we can obtain similarity properties of the plasma and compare them with astrophysical jets. In order to predict and understand the jet evolution we try to find self-similar solutions with the Burgan-Feix transformation (Burgan 1978) we will describe later. In the first part, we focus on the theoretical hydrodynamic model and present the solutions. In the second part, we compare the analytical results with laboratory jets experiments which will allow us to predict the structure of jets.

## 2 The Burgan-Feix transformation and hydrodynamic expansions

The problem of expanding fluids in vacuum has many applications in astrophysics (for instance, the first phase of supernova remnant evolution (Ribeyre et al. 2006)) and in laser experiments (Murakami et al. 2005). Several Self-Similar Solutions (SSS) to this problem have been seeked. SSS play a key role in many domains of physics and astrophysics. These solutions give fundamental information about the physical systems we study and are an essential complement to numerical simulations (validation and understanding). Several approaches, based upon properties of invariance or partial invariance (Ovsjannikov 1978), exist and provide several classes of solutions compatible with only specific initial conditions (IC). In order to make sure that the solutions will be compatible with any boundary and/or IC, Burgan and Feix (Burgan 1978) derived a transformation group - which we

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name the Burgan-Feix Transformation (BFT)- based upon the concept of partial invariance. Using the physical conformity principle, it is possible to give a particular physical meaning to all the self-similar transformations presented in the literature (Falize et al. 2007). The BFT also allows the derivation of new solutions through more complex analytical calculations. The BFT connects the physical space-time $(r,t)$ to the transformed space-time $(\hat{r},\hat{t})$, also named the *rescaled space* and labelled $(R_d)$ through the relations: $dt = A^2[t]d\hat{t}$ and $r = C[t]\hat{r}$, where $A$ and $C$ are two scaling functions. Conventionnally, all the physical quantities in $(R_d)$ are labelled with a hat "$\wedge$". These relations imply that $v = (C[t]/A^2[t])\hat{v} + (\dot{C}[t])\hat{r}$ since $\hat{v} = d\hat{r}/d\hat{t}$ (the upper dot "." stands for the time derivative) and, in addition, we have $P(r,t) = B[t]\hat{P}(\hat{r},\hat{t})$ and $\rho(r,t) = D[t]\hat{\rho}(\hat{r},\hat{t})$ where $P$ and $\rho$ are respectively the pressure and density and B[t] and D[t] are two more scaling functions. The only constraint we have is that $A[0] = B[0] = C[0] = D[0] = 1$, implying that IC are preserved from (r,t) to $(\hat{r},\hat{t})$. The application of BFT on the hydrodynamic equations gives:

$$\frac{d\rho}{dt} + \frac{\rho}{r^d}\frac{\partial}{\partial r}(r^d v) = 0 \leftrightarrow \frac{d\hat{\rho}}{d\hat{t}} + \frac{\hat{\rho}}{\hat{r}^d}\frac{\partial}{\partial \hat{r}}\left(\hat{r}^d\hat{v}\right) + A^2[t]\left(\frac{\dot{D}[t]}{D[t]} + (1+d)\frac{\dot{C}[t]}{C[t]}\right)\hat{\rho} = 0 \tag{2.1}$$

$$\frac{dv}{dt} = -\frac{1}{\rho}\frac{\partial}{\partial r}P \leftrightarrow \frac{d\hat{v}}{d\hat{t}} + 2A^2[t]\left(\frac{\dot{C}[t]}{C[t]} - \frac{\dot{A}[t]}{A[t]}\right)\hat{v} + \frac{\ddot{C}[t]A^4[t]}{C[t]}\hat{r} = -\frac{B[t]A^4[t]}{D[t]C^2[t]}\frac{1}{\hat{\rho}}\frac{\partial}{\partial \hat{r}}\hat{P} \tag{2.2}$$

$$\frac{dP}{dt} - \gamma\frac{P}{\rho}\frac{d\rho}{dt} = 0 \leftrightarrow \frac{d\hat{P}}{d\hat{t}} - \gamma\frac{\hat{P}}{\hat{\rho}}\frac{d\hat{\rho}}{d\hat{t}} + A^2[t]\left(\frac{\dot{B}[t]}{B[t]} - \gamma\frac{\dot{D}[t]}{D[t]}\right)\hat{P} = 0 \tag{2.3}$$

where $\gamma$ is the polytropic index, $d/dt$ is the Lagrangian derivative and $d$ is the dimension parameter (d=0,1,2 in plane, cylindrical and spherical geometry, respectively). Additionnal terms appear in "$\wedge$" equations (2.1), (2.2) and (2.3), and the physical conformity principle implies that $(R_d)$ is interpreted as a physical space where all the additional terms have a physical interpretation [source in (2.1) or (2.3), friction in (2.2)] and all the quantities preserve their physical meaning. Since the rescaled equations have more complexity and, therefore, more richness (we can break standard symmetries), we are going to look for simple, *i.e.* static, solutions ($\hat{v} = 0$ and $\partial/\partial\hat{t} = 0$) in $(R_d)$. This requirement implies that $v(r,t) = (\dot{C}[t]/C[t])r$ which is usually an *ad hoc* assumption in several papers (Murakami et al. 2005). We look for static solutions and the time dependent coefficients in (2.1), (2.2) and (2.3) should be zero or constant. From (2.1) and (2.3), we obtain respectively $D[t] = C^{-(1+d)}[t]$ and $B[t] = D^{\gamma}[t]$ with $\hat{P}[\hat{r}]\hat{\rho}^{-\gamma}[\hat{r}] = \kappa[\hat{r}]$ where $\kappa[\hat{r}]$ is an arbitrary function. From (2.2), we get $B[t]A^4[t]/(C^2[t]D[t]) = 1$ and $\ddot{C}[t]A^4[t]/C[t] = \pm\Omega^2$ where $\Omega$ is a constant, the dimension of which is the inverse of a time. For the sake of simplicity, the entropy is assumed to be constant and we have $\hat{\kappa}[\hat{r}] = \kappa_0$. Considering the experimental situation, we keep only convergent (maximum density in $\hat{r} = 0$) solutions which correspond to $\ddot{C}[t]A^4[t]/C[t] = \Omega^2$. Integrating the static version of (2.2) in $(R_d)$, we deduce:

$$\rho(r,t) = \frac{\rho_c}{C^{1+d}[t]}\left[1 - \left(\frac{r}{R_0 C[t]}\right)^2\right]^{1/(\gamma-1)}, \gamma \neq 1; \quad \rho(r,t) = \rho_c exp[-(r/C[t])^2], \gamma = 1, \tag{2.4}$$

where $R_0$ is the initial radius and $\rho_c = \rho(0,0)$. Moreover, combining the four constraints for the four scaling functions gives $\ddot{C}C^{1+(d+1)(\gamma-1)} = \Omega^2$ which is a particular Emden differential equation. The implicit solutions are

$$C \times \left({}_2F_1\left[\frac{1}{2}, \frac{1}{(1+d)(1-\gamma)}; \frac{1+(1+d)(1-\gamma)}{(1+d)(1-\gamma)}; C^{-(d+1)(\gamma-1)}\right]\right) \propto (t - t_0) \tag{2.5}$$

for $\gamma \neq 1$, where ${}_2F_1$ is Gauss hypergeometric functions. For $\gamma = 1$ we obtain:

$$Erfi\left[(1/\Omega\sqrt{2})\sqrt{(a_1 + 2\Omega^2 ln[C])}\right] = \sqrt{2/\pi} \times exp\left[(a_1/2\Omega^2)\right]\Omega(t - t_0) \tag{2.6}$$

where $Erfi$ is the imaginary error function. We compare these solutions with Runge-Kutta calculations (see figure 1) in order to validate our numerical values of hypergeometric functions and Erfi function.

If we impose that the physical system satisfies the projective Lie symmetry $[\gamma = (d+3)/(d+1)]$, we obtain the peculiar solutions of (Ribeyre et al. 2006). Bernouilli theorem leads to $\Omega = [\sqrt{2/(\gamma-1)}]c_{s,0}/R_0$, where $c_{s,0}$ is the sound speed at the center of the system.

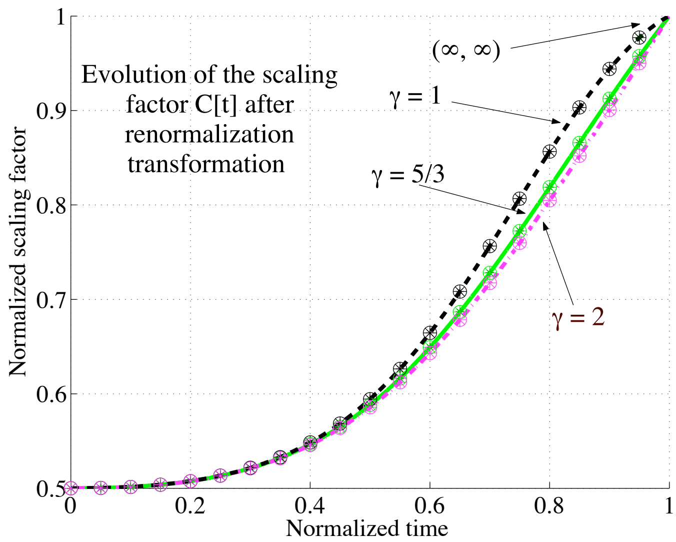


**Fig. 1.** Comparison between analytical solutions (color lines) and Runge-Kutta calculations (color points) for different values of $\gamma$. We applied a projective transformation on the equation in order to integrate the equation on finite segment.

## 3 Comparison with laboratory jet experiments

The target is composed by a three layer pusher (Al/ CH/ Ti) from laser side and a cone filled with foam at different densities. We can use high-Z material doped foam in order to create a more radiative jet and decrease the radiative cooling time. We use the two LULI2000 beams (wavelength 527 nm, spot diameter 500 $\mu$m , pulse duration 1.5 ns and intensity $I_L \sim 10^{14}$ W.cm$^{-2}$) that we focused onto the pusher to generate by rocket effect a shock that propagates through the foam (Loupias et al. 2007). The cone geometry allows us to drive the plasma flow along the cone axis to create the jet. Similarity analysis shows that thermal flux and cooling effects are negligible and thus compatible with a hydrodynamic model. We created supersonic jets ($M \sim 10$) which are dynamically relevant for astrophysics jets where space and time scales are linked by: 100$\mu$m $\rightarrow 7 \times 10^{-3}$ pc and 1 ns $\rightarrow 10^3$ years.

We observed a radial expansion of created jets (Loupias et al. 2007). We consider the jet as a cylinder with an infinite length. In order to predict the observed results on the self-emission diagnostic, we must choose a T-isothermal curve evolution. Thus, we introduce a thermal radius (that we note $R_{th}$) which is defined by the position where the temperature of plasma is T. With this definition, it is easy to obtain analytical expression for $R_{th}$ which is $R_{th}(t) = R_0 C[t]\sqrt{1 - \eta(C[t])^{2(1-\gamma)}}$, where $\eta = T/T_c$ and $T_c$ the initial central temperature. Fitting the experimental data, we can obtain $T_c$. On figure 2, we see a very good agreement between experimental data and theoretical prediction. Given that $T \sim 0.5$ eV and $\eta = 0.033$ we predict $T_c \sim 15$ eV. This value is compatible with simulation results. We also see, on figure 2, that there is a difference between hydrodynamic and thermal radius. Thus, the jet possesses a shell structure with a cold shell which surrounds a hot core.

## 4 Conclusion

We obtained the full analytical solutions for expanding collisional plasmas into vacuum. The key parameters of the jets can be compared with experiments and we can predict the observation of the self-emission diagnostic signal. The future introduction of ambiant medium will allow us to study a class of expanding jets equivalent to HH 30 (Hartigan & Morse 2007). We will also try to increase the radiative properties of these jets to see the effects of the radiation losses on the collimation properties and compare them with the theoretical predictions (Falize et al. 2007).

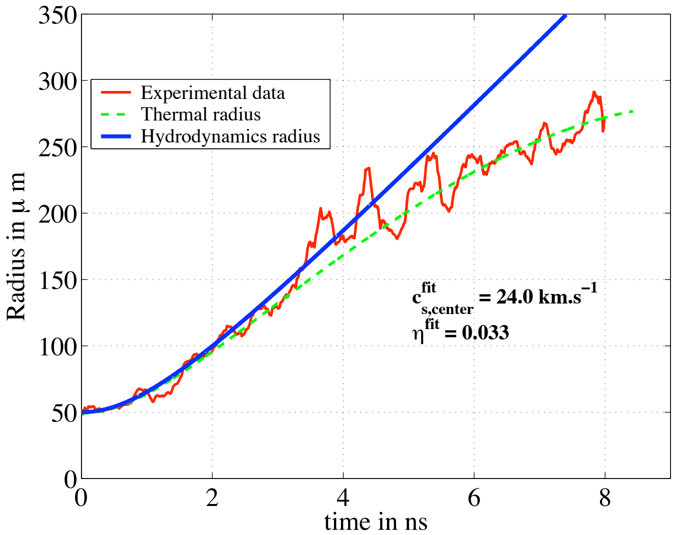


**Fig. 2.** Comparison between experimental and theoretical thermal radius ($R_{th}$). This quantity is derived from self-emission diagnostic (Loupias et al. 2007) by choosing a T-isothermal curve where $R_{th}(t) = R_0 C[t]\sqrt{1-\eta(C[t])^{2(1-\gamma)}}$ and $\eta = T/T_c$ with $T_c$ the initial central temperature. $c^{fit}_{s,center}$ corresponds to initial (t=0) center (r=0) sound velocity.

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