A SHOCK WAVE THEORY OF "SUPER-LUMINAL" OUTBURST FROM AGN

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ABSTRACT. Dynamics is investigated of relativistic blast waves in the neighborhood of active galactic nuclei (AGN). The inverse cubic decrease of the density is considered corresponding to the hydrostatic equilibrium of the relativistic media with the equation of state $p \propto \rho^{4/3}$ in the vicinity of a big point mass. For the off-center ultra-relativistic point explosion the Lorentz factor of the leading point of the shock front is proved to have an asymptotically constant value that explains the observed super-luminal relativistic velocities of jets' components of 3C 345(Babadjanjanz, Belokon',1985; Belokon', 1991). It is also found that for the leading point moving at small angles to the direction of sight the apparent super-luminal velocity linearly depends on the energy of explosion, which is in a good agreement with the observations for 3C 273(Babadjanjanz, Belokon',1993).

Key words: AGN: bursts, superluminal jets; shocks: ultra relativistic, blast wave.

1. Introduction. Off-Center Relativistic Adiabatic Explosion

Among objects of the contemporary radio astronomy explosion processes with extremely high energies are of particular interest such as Supernova (or even Hypernova) explosions (Waxman & Loeb, 1998), gamma-bursts (Paczynski, 1999) and outbursts from AGN — jets (Begelman, Blandford & Rees, 1984). In these cases motions have relativistic or even ultra-relativistic velocities (see for example the review by Vermeulen and Cohen, 1994 for the super-luminal sources, where the velocities of jet components are given): that boosts interest in investigations of dynamics of relativistic blast waves (Blandford and McKee, 1976, 1977). As follows from the conditions of the hydrostatic equilibrium the density decrease in the vicinity of AGN obeys the inverse cubic law. The adiabatic model of explosions is considered — the medium believed nonviscous, with no thermal conductivity and no interaction with magnetic field or radiation. This work is based on the Kompaneets approximation for the relativistic motion (Shapiro, 1979, 1980). The Kompaneets equation for SF is generally speaking (nonlinear) integro-differential one due to the volume of spreading hollow within the SF it contains. The volume expression contains time depending coordinates of the leading points limiting the SF in the direction of the density gradient. In non-relativistic case (Kompaneets, 1960; see also the review of Bisnovatyi-Kogan and Silich, 1995 and Kontorovich and Pimenov, 1997, 1998) the volume is only as multiplier at time derivative and can be by including in the new variable ("Kompaneets time") removed from the coefficients of the equation. In the relativistic case the similar volume exclusion is impossible, the equation is essentially integro-differential. But in ultra-relativistic limit, when the SF movement proceeds at a speed rather close to the velocity of light, the SF form is quite close to the sphere of the radius *ct* and the hollow volume present in the equation is thus known. In this case however the aim of the calculation is Γ-factor, which can be expressed through the media density in the point crossed by the SF (see below). For a strong explosion the relation is valid $p_2/n_2 \gg p_1/n_1$, where $n_{1,2}$ and $p_{1,2}$ are the concentration and pressure before and after the shock front in the comoving reference frame of the fluid, correspondingly. According to this relation the average kinetic energy of particles is much greater behind the shock front (SF) than it is in front of it. Consequently, the pressure in front of the SF can be neglected. As the density at the explosion point is finite, the Sedov's stage of deceleration exists for early stages of expansion with the uniform distribution of flow parameters and Lorentz factor. At later stages the value of the Lorentz factor can change essentially along the SF.

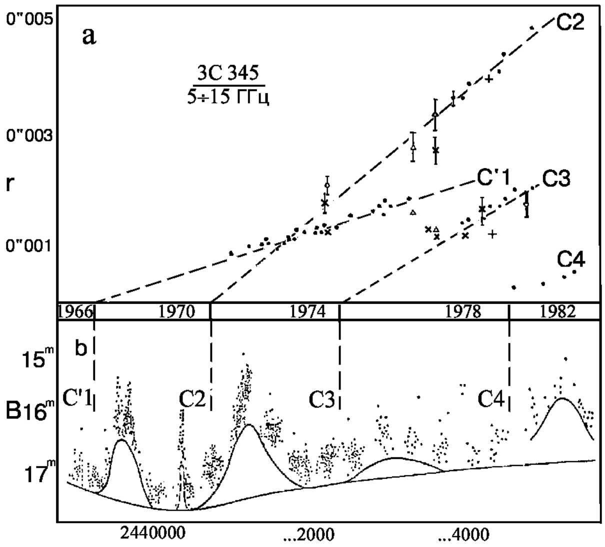

Figure 1: A correlation is seen between the super-luminal velocity components and the optical bursts that can witness their explosion origin (BB85). The jet components are observed moving at constant ultra-relativistic velocities in accordance to the result below.

2. Observational Data of Super-Luminal Velocity Components in Quasars

Yet the authors of VLBI observations, who revealed the occurrence of "super luminal components", were searching for (and would never found) the events in RADIO variability (for the total radio flux from the object), which would correspond to the component formation in millisecond jets (3 273 3 120, 3 345). Such evidences were first found (though for variability in OPTICS) at 3 345, 3 120, 3 273, OJ 287 Babadjanjanz and Belokon' (BB85). Later similar relations was found both in optics and in radio: Bregman, et al., 1986, 3C 345 (radio, mm), Krichbaum, et al., 1990, (IR-optical flare), Mutel, et al., 1990, (BL Lac, radio), Zenzus, et al., 1990, 3 273 (radio), etc. Recently the correlation of formation of super luminal components with gamma bursts has been reported (see as example Pohl, et al., 1995, 0528+134, etc). Therefore, it is possible, that some sources release their most energy of bursts, which accompany the components, in the X- and gamma-ranges. The evaluation of burst energy release are impeded also by their complex structure. Below we will rely upon the Leningrad team's data with allowance for the made reservations.

The interpolation trajectories are shown in Fig.1 of ultra-relativistic velocity components of the jet 3 345. Their apparent velocities can be explained by relativistic effects of motion at the small angles to the direction of sight.

Apparently, the only result, which argues in favour of correlation between the burst energy release and the speed of the flare-related component, is yet adduced in the article on 3 273 (Fig. 4 and Fig. 5 in BB93). On the fig 4 for 3C273 from BB93 the dependence is clearly seen: the greater the intensity of optical radiation at the initial stage, the greater the apparent super-luminal velocity. In Fig.2 the dependence of the apparent super-luminal velocity on the optical activity and, correspondingly, the optical flux density F at the stage of separation of components from the nucleus is presented for the components 2 – 9 of the millisecond radio jet 3 273 (BB93).

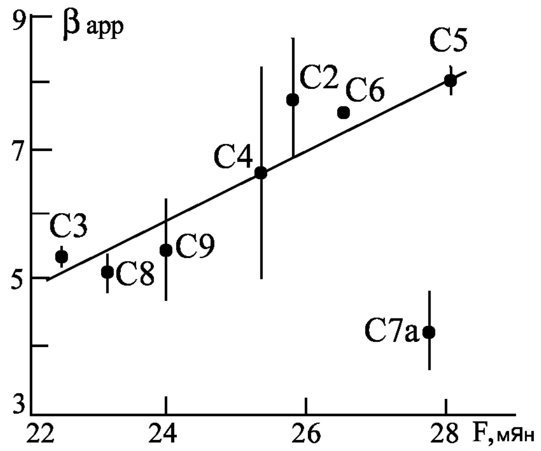

Figure 2: The linear dependence is observed of the apparent super-luminal velocity on the energy density of the optical radiation flux (BB93).

3. The Ultra-Relativistic Blast Shock Wave

The necessary condition for the motion to be relativistic is given by the expression $E \gg \rho_1 V c^2$, i.e. the energy of explosion is much more than the rest energy of gas within the envelope. For the adiabatic explosion the following relations are true at the SF (Blandford R.D. & McKee C.F., 1976):

$$p_2 = e_2/3 = 2\Gamma^2 w_1 c^2, \quad n_2' \equiv \gamma_2 n_2 = 2\Gamma^2 n_1, \qquad (1)$$

$$\gamma_2^2 = \Gamma^2/2, \quad \Gamma = 1/\sqrt{1 - v^2/c^2}.$$

Here p_2, e_2, n_2 are the pressure, the density of energy and the concentration of particles in the reference frame of pre-shock and post-shock flows, correspondingly. The values n_2', γ_2, w_1 , are the concentration of particles, the Lorentz factor of the flow behind the SF and the density of external media in the frame of the unshocked gas, accordingly (for a cool gas $w_1 = n_1 m_1$). For the explosion processes in question the values of parameters are sensitive to a small difference between of the velocity of light and the SF one. There is the Lorentz factor of the SF that characterizes this difference and describes observational values. That is why it is important to know the time dependence of the Lorentz factor along the SF.

4. The Relativistic Kompaneets Approximation.

This approximation describes the qualitative dynamics of SF adequately at the exponent $n \leq 3$ (Shapiro P.R., 1980) in the law of density decrease. The pressure behind the SF in the reference frame of post-shock is suggested uniform along the SF and proportional to the average density of the explosion energy.

$$p_2 = \lambda E/V \tag{2}$$

where E is the explosion energy, V is the volume restricted by the envelope and $\lambda =$ const that is taken from the self-similar solutions (Shapiro P.R., 1979).

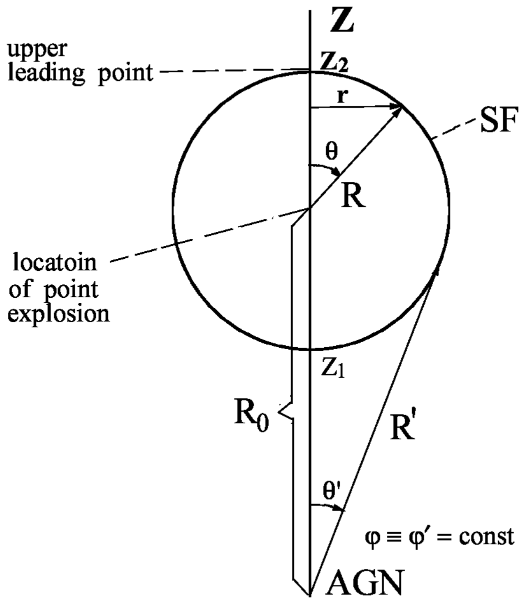

Figure 3: The shock front and the reference frame

Analytically the velocity $\beta = v/c$ of the SF motion is described in the cylindrical coordinates (r, z) as follows

$$\beta = \dot{r}/c\sqrt{1+r_z^2}, \quad r_z \equiv \partial r/\partial z. \tag{3}$$

From the relations at the SF (1) and the Kompaneets approximation condition (2) the equation of the SF motion follows (Blandford and McKee 1976):

$$\dot{r}/\sqrt{1+r_z^2} = c\left[1 - \frac{2w_1(r,z)V(t)c^2}{3\lambda E}\right]^{1/2}. \tag{4}$$

5. The Ultra-Relativistic Explosion in the Vicinity of AGN

In the spherical coordinates (R', θ') with the center in the AGN the density of external media is $w_1 = a/R'^3$, $a =$const > 0 in the range $R_* < R' \ll R_{ef}$ where R_* is a radius of the galactic nucleus, R_{ef} — is such a distance from the nucleus for which either the mass of the external medium inside the sphere of this radius is equal to the nucleus mass or the media becomes non-relativistic. Note that in this consideration we completely neglect the movement of media due to accretion on the central compact object (Blandford 1999, Shakura 1974) or ejection in the jet or wind that can affect as directly as through the density distribution.

In the reference frame of the nucleus the coordinates of the explosion point are $(R_0, 0)$. Consider a new system of spherical coordinates (R, θ) with the center at the explosion point and the polar axis directed towards the upper leading point of the SF. The shape of the SF is close to a sphere at least for $t < t_* \leq R_0/c$ where t_* is the time since that the motion of the lower leading point can not be ultra-relativistic. We can estimate the volume $V \approx 4\pi t^3/3$ restricted by the SF and the density of external medium w_1:

$$w_1 \approx a(t^2 + R_0^2 + 2tR_0\cos\theta)^{-3/2}. \tag{5}$$

From the conditions (1) and (2) the explicit expressions for the Lorentz factor of the SF can be written as

$$\Gamma^2 \approx \frac{(t^2 + R_0^2 + 2tR_0\cos\theta)^{3/2}}{2Bt^3}, \quad B = \frac{4\pi ac^2}{9\lambda E}. \tag{6}$$

At larger times as the SF lower leading part approaches the radius of the nucleus R_* this part decelerates and the shock front becomes non-spherical (cf. Kontorovich, Pimenov, 1997, 1998). Nevertheless, at least for the SF upper leading part the relation (6) remains true. It can be proved that if the size of the central mass is negligible compared to the size of the envelope than the relative deviation of the volume of its estimation is small enough $\Delta V_s/V = O(\Gamma^{-4/3})$.

Instead of the Kompaneets approximation any version of the sector approximation can be used (Laumbach and Probstein 1969, Shapiro 1979, Gnatyk 1987, Gnatyk and Petruk 1996). It can be shown that because the shape of the SF in the vicinity of the upper leading point is close to a part of a sphere the expressions of the Lorentz factor found in Blandford and McKee 1976 and Shapiro 1979 coincides with (6).

If time t approaches infinity the relation (6) gives an asymptotically constant value of the Lorentz factor of the upper leading part of the SF.

$$\Gamma^2 \overset{t\to\infty}{\longrightarrow} \frac{1}{2B}. \tag{7}$$

Note that the asymptotic expression (7) is an intermediate one because time is restricted by the inequality $t \ll R_{ef}/c$.

6. The Dependence of Ultra-Relativistic Velocities on the Energy of Explosion

It is known (see Begelman M.C., Blandford R.D. & Rees M., 1984) that the apparent super-luminal velocity of a source moving at a small angle to the line of sight is equal to

$$\beta_{app} = \frac{\beta \sin\alpha}{1-\beta\cos\alpha} \xrightarrow{\alpha \ll 1} \frac{2\alpha}{1/\Gamma^2 + \alpha^2}, \qquad (8)$$

where β is the real velocity of motion

$$1 - \beta \approx 1/2\Gamma^2 \ll 1.$$

Considering the energy of explosion E as a parameter the relation in the vicinity of the upper leading point can be reduced to the expression

$$\beta \approx 1 - \frac{4\pi a t^3 c^2 (t^2 + R_0^2 + 2tR_0\cos\theta)^{-3/2}}{9\lambda E}. \qquad (9)$$

At larger times due to the asymptotic approach of the Lorentz factor to a constant value the multiplier at E^{-1} in (9) can be considered constant as well that allows representing the relation (9) as follows

$$\beta \approx 1 - \frac{A}{E}, \quad A = \frac{4\pi a c^2}{9\lambda}, \quad (\Gamma^2 \approx \frac{E}{2A}). \qquad (10)$$

For small enough angles $\alpha \ll 1/\Gamma$ Lorentz factor defined by the relation (10) can be substituted into the right side of the equation (8). The final expression for the apparent super-luminal velocity of the motion is

$$\beta_{app} \approx \alpha A^{-1} \cdot E. \qquad (11)$$

Thus, the apparent super-luminal velocity of the SF upper leading point is proportional to the explosion energy. In the case of nonconstancy (variability) of the angle α or the necessity of the averaging on it the energy dependence of the apparent component velocity has to change. As example for simple integrating on the angle this dependence will be logarithmic: $\beta_{app} \propto \ln E$.

7. Conclusion

1. For the model of the ultra-relativistic explosion in the vicinity of an AGN the Lorentz-factor of the SF leading point is proved to approach asymptotically to a constant. This result is in a good agreement with the observational data of ultra-relativistic velocities of jets' components (BB85, BB94, Belokon', 1991).
2. In the same model at the assumption that the leading part of the ultra- relativistic SF moves at a small angle to the line of sight the linear dependence is found of the apparent ultra-relativistic velocity of the leading part on the explosion energy. This result explains the observational values of apparent velocities of jets' components (BB93) at the suggestion about a proportionality between the optical energy flux at the moment of the components' origin and the explosion energy.

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