THE EFFECT OF COLLIMATION ON THE APPEARENCE OF RELATIVISTIC JETS

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Abstract:

The question of the collimation of relativistic jets is the subject of a lively debate in the communauty. It is partly obscured by the absence of a precise definition of a collimation criterion. We argue that, if the motion is relativistic, the high superluminal velocity are possible only if θ_j is smaller than the relativistic beaming angle γ^{-1}. In the opposite case, the apparent image will be dominated by the part of the jet travelling directly towards the observer. Furthermore, we show that the appearence of a jet is highly dependent on the jet velocity structure. We numerically calculate the apparent velocity and the Doppler factor of a jet for different structures.

Jet kinematics:

To model the jet appearence, we consider the simple case of a **spherical surface** propagating with a relativistic speed caracterized by a **bulk Lorentz factor** γ_0 on the jet axis. **The geometrical collimation is characterized by the angle** θ_j and we study four different distributions of γ that depend on θ, the angle from the jet axis. These distributions are also used in the GRB context (Dyks et al 2005).

D1: $\gamma(\theta)=\gamma_0$ if $|\theta|<\theta_j$ and $\gamma(\theta)=0$ else (Fig. 2a)

D2: $\gamma(\theta)=\gamma_0$ if $|\theta|<\theta_j$ and $\gamma(\theta)=1+(\gamma_0-1)(\theta/\theta_j)^{-2}$ else (power law Fig. 3a)

D3: $\gamma(\theta)=1+(\gamma_0-1)\exp(-(\theta/\theta_j)^2)$ for every θ (gaussian distribution Fig. 4)

D4: $\gamma(\theta)=1+(\gamma_0-1)/(1+(\theta/\theta_j)^2)$ for every θ (lorentzian distribution Fig. 4)

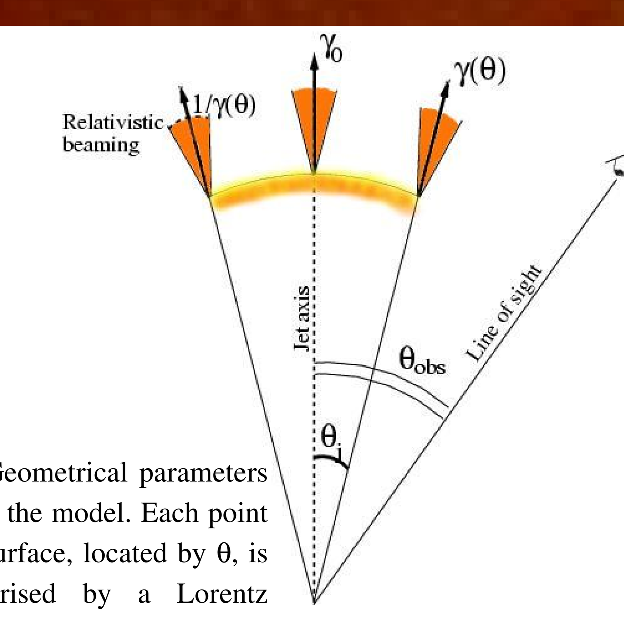

Fig. 1-Geometrical parameters used for the model. Each point of the surface, located by θ, is characterised by a Lorentz factor $\gamma(\theta)$.

Methods:

The jet is characterized by γ_0, θ_j and the bulk Lorentz factor distribution. Then, we set θ_{obs} **that is the angle between the line of sight and the jet axis**. We compute the apparent velocity and intensity of each point of the surface seen by the observer, taking into account all kinematic effects that affect the observed flux (Doppler boost, propagation time delays). **The jet apparent velocity β_{app} (in unit of c) and the Doppler amplification $\mathcal{D}$, are defined by the brightest point of the surface.**

Thus, for a jet configuration, we plot β_{app} and $\mathcal{D}$ versus θ_{obs} and determine **the maximum apparent velocity $\beta_{app,max}$ that can be reached**. Then, we calculate some abacus, that represent $\beta_{app,max}$ and $\mathcal{D}$ versus γ_0 and θ_j for different distributions.

RESULTS

D1 distribution: $\gamma(\theta)=\gamma_0$ if $|\theta|<\theta_j$ and $\gamma(\theta)=1$ else

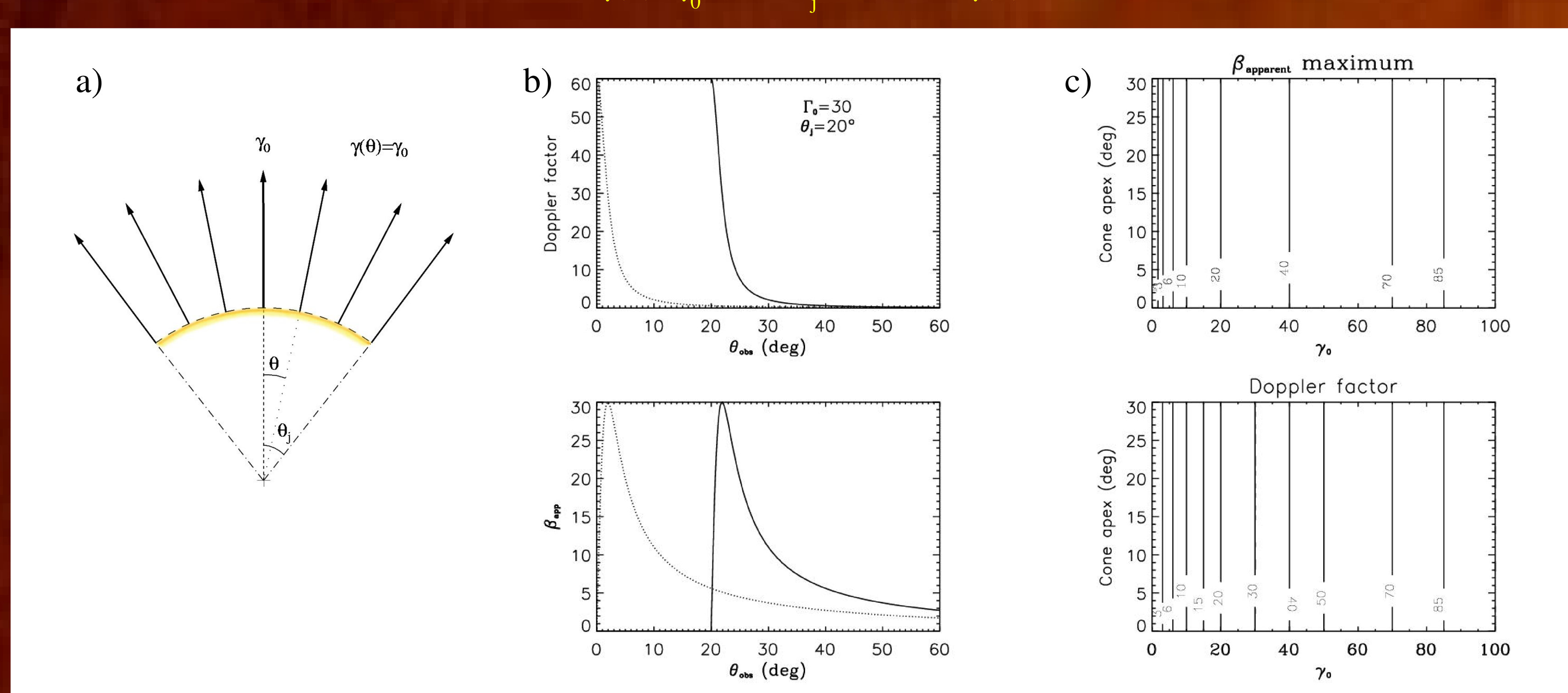

Fig. 2- a)D1 distribution. b)The solid lines are the Doppler factor (up) and apparent velocity (down) of a jet characterized by a bulk Lorentz factor γ_0=30 on the jet axis, an opening angle of 20°. The dotted lines are for an ideally collimated jet. c)abacus that represent the maximal apparent velocity $\beta_{app,max}$ that can be reached with a jet characterized by γ_0 and θ_j (up), and the associated Doppler factor (down).

For the distribution D1, the result is intuitive. If we look inside the jet ($\theta_{obs}<\theta_j$), the image seen on the sky by the observer is dominated by the brightest component which is moving directly toward us. Hence, the apparent velocity of the jet is null, and the Doppler boost is maximum ($2\gamma_0$). Once we look outside the jet ($\theta_{obs}>\theta_j$), we are dominated by the edge of the jet, and **the situation is similar to a bulk with a perfect collimation (θ_j=0°) seen with an angle of $\theta_{obs}-\theta_j$**. This is illustrated on Fig. 2b which represents β_{app} and $\mathcal{D}$ versus θ_{obs} for γ_0=30, in the ideal case (cylindrical collimation-dotted lines) and for θ_j=20° (solid lines). Therefore, D1 distribution is able to give high superluminal velocity if we look close to the edge of the jet, where we have $\beta_{app,max} \sim \gamma_0$ for $\theta_{obs} \sim \theta_j + \gamma_0^{-1}$ and $\mathcal{D} \sim \gamma_0$ for every θ_j and γ_0. This is illustrated by the two abacus, where the contours are vertical lines with the value of the Lorentz factor (Fig. 2c).

D2 distribution: $\gamma(\theta)=\gamma_0$ if $|\theta|<\theta_j$ and $\gamma(\theta)=1+(\gamma_0-1)(\theta/\theta_j)^{-2}$

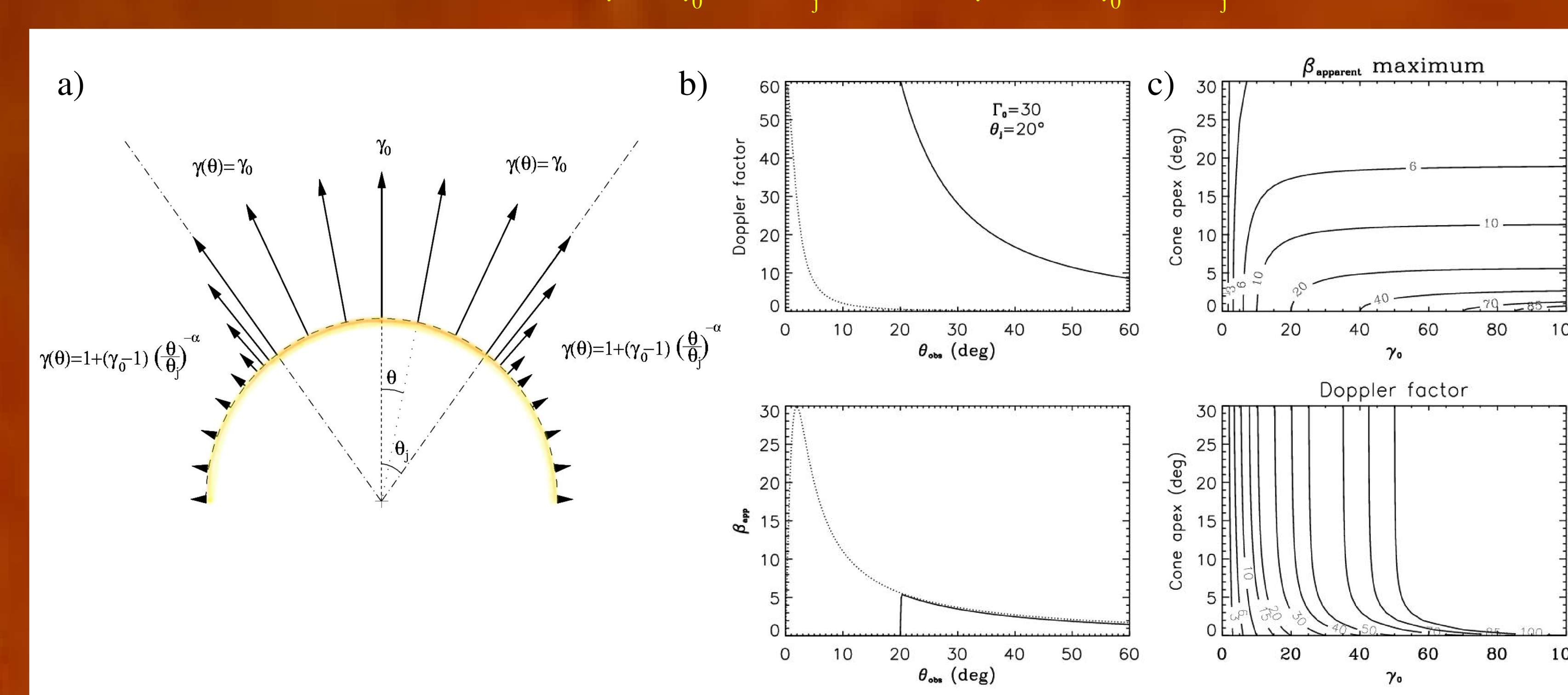

Fig. 3- a)D2 distribution: power law. b)Doppler factor (up) and apparent velocity (down) of a jet characterized by a bulk Lorentz factor γ_0=30 on the jet axis, an opening angle of 20° in solid lines. The dotted lines are for an ideally collimated jet. c)abacus that represent the maximal apparent velocity $\beta_{app,max}$ that can be reached with a jet characterized by γ_0 and θ_j (up), and the associated Doppler factor (down).

We can see on Fig. 3b. the effect of a continuous distribution of Lorentz factor as D2 distribution. Once again, β_{app} vanishes when the observer looks inside the cone, but as soon as he looks on the edge of the jet, the brightest point of the jet moves away the line of sight, giving an apparent motion. **β_{app} is smaller than the D1 case because the brightest point has a lower Lorentz factor than on the jet axis, and because it is seen very closed to the line of sight.** This fact is confirmed by the Doppler factor associated to $\beta_{app,max}$ which is closed to $2\gamma_0$. It is visible on the abacus (Fig. 3c) that $\beta_{app,max}$ can be higher if the collimation is better than γ_0^{-1}. Indeed, **for a given γ_0, the contour begins by a vertical line which curves as soon as the geometrical collimation angle exceeds γ_0^{-1}.**

D3 distribution (Gaussian): $\gamma(\theta)= \gamma(\theta)=1+(\gamma_0-1)\exp(-(\theta/\theta_j)^2)$

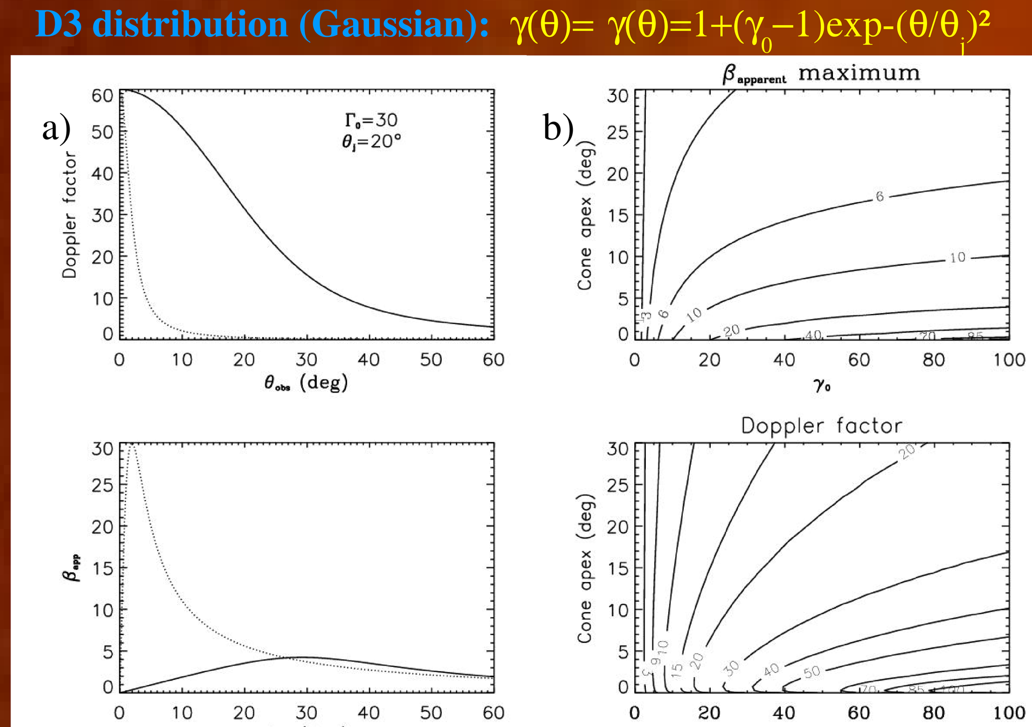

Fig. 5- a)Doppler factor (up) and apparent velocity (down) of a jet characterized by a bulk Lorentz factor γ_0=30 on the jet axis, an opening angle of 20°, in solid lines. The dotted lines are for an ideally collimated jet. b)abacus that represent the maximal apparent velocity $\beta_{app,max}$ that can be reached with a jet characterized by γ_0 and θ_j (up), and the associated Doppler factor (down).

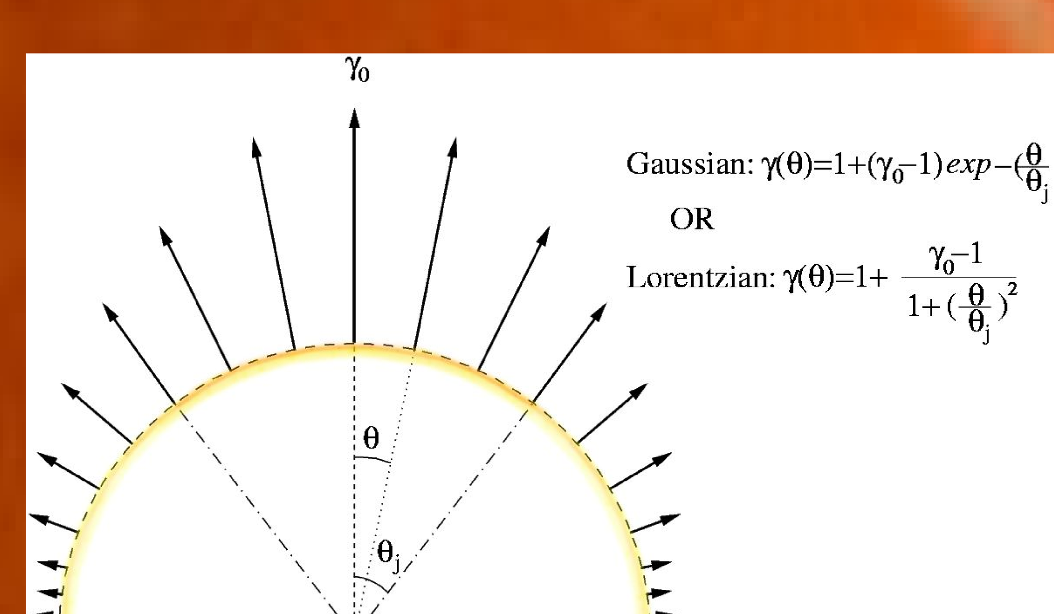

Fig.4.-D3 (D4 respectively) distribution; The Lorentz factor distribution is a gaussian fonction (lorentzian respectively).

D4 distribution (Lorentzian): $\gamma(\theta)=1+(\gamma_0-1)/(1+(\theta/\theta_j)^2)$

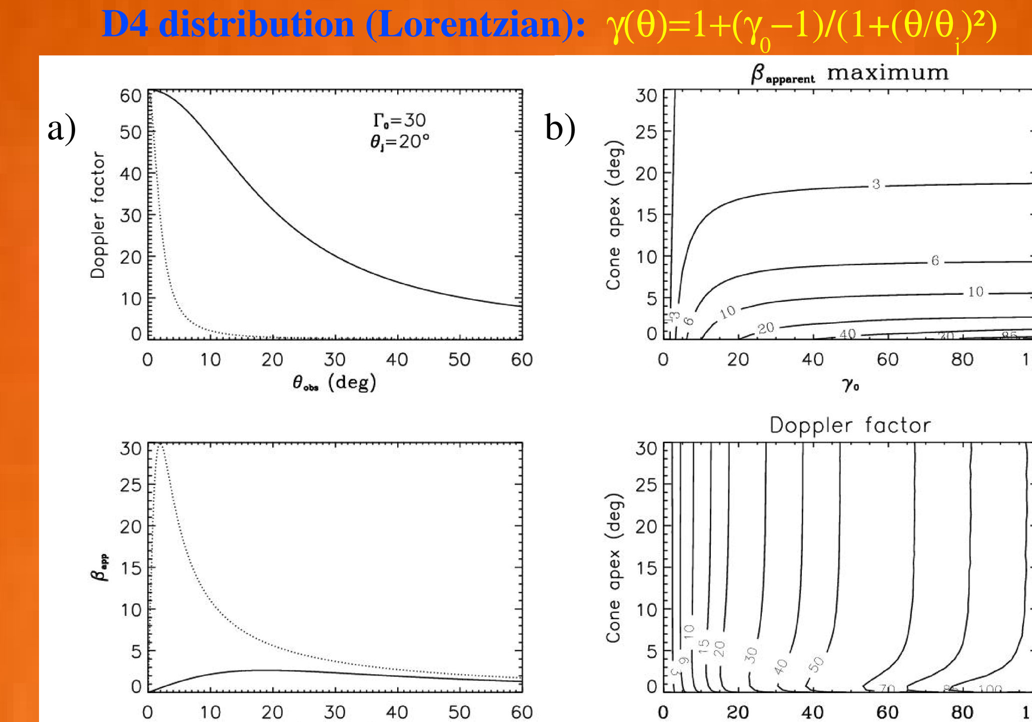

Fig. 6- a)Doppler factor (up) and apparent velocity (down) of a jet characterized by a bulk Lorentz factor γ_0=30 on the jet axis, an opening angle of 20°, in solid lines. The dotted lines are for an ideally collimated jet. b)abacus that represent the maximal apparent velocity $\beta_{app,max}$ that can be reached with a jet characterized by γ_0 and θ_j (up), and the associated Doppler factor (down).

For D3 and D4, we can see on Fig. 5a and Fig. 6a that for these kind of distriutions, **when the Lorentz factor is never constant, β_{app} is non-null for evry θ_{obs}**. This is because the brightest point of the jet is never on the jet axis. The maximum apparent velocity is reached when θ_{obs} is slightly greater than θ_j. For a given configuration, we can notice that $\beta_{app,max}$ is greater for the gaussian distribution than for the lorentzian one. The study of the abacus that represent $\beta_{app,max}$ versus the jet parameters for D3 and D4 (Fig. 5b and Fig. 6b) leads to the same conclusion as D2. In fact, it appears that the value of $\beta_{app,max}$ **is connected to the gradient of the distribution around the line of sight**. Indeed, when the observer looks where the distribution is constant, β_{app} is null, and when the variation is maximum (near the jet edge for the D1 distribution), $\beta_{app,max}$ reached the theoretical level.

Conclusion:

These simulations show that the apparent speed is very sensitive to the collimation of the jet, and that it drops dramatically as soon as the collimation is non-null. So, the collimation of a relativistic jet must be very good to be able to produce the very fast superluminal sources that are actually observed (Piner et al, 2005, measured apparent speeds exceeding 25c).

If we look at the constraints given by the lorentzian distribution D4, we see that the geometrical collimation must be better than the inverse of the apparent speed in unit of c. This relation is holds approximately for the other distributions within a factor 2 or 3, and can be used to have an upper limit of the jet aperture, by measuring the superluminal motion. So we have the following relation:

$$\text{Collimation angle} < 1/\beta_{app}$$

References:

Dyks, J., Bing Zhang, Fan, Y.Z., 2005, preprint (astro-ph/0511699)

Piner, B.G., Bhattarai, D., Edwards, P.G., Jones, D.L., 2005, preprint(astro-ph/0511664)