The power of jets: blazars vs galactic superluminals

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Abstract. Estimates on different scales of the power of relativistic bulk motion in extragalactic and galactic jets are presented. The power in the jets and the power produced by the accretion disk are found to be roughly equal. This may suggest an important role of the magnetic field in extracting both the gravitational energy of the accreting matter and the rotational energy of the black hole. A method to derive the minimum power of jets is discussed, and used to find lower limits to the jet power of blazars and the galactic superluminal source GRS 1915+105. The matter content of jets is discussed, finding that electron positron pairs cannot be dynamically important. The jet power can initially be in the form of Poynting flux, gradually accelerating matter until equipartition between bulk motion of the particles and Poynting flux is reached.

1. Introduction

Special relativity is important to study fundamental particles in terrestrial accelerators, but it is also the key to understand large scale phenomena involving thousand of solar masses traveling at nearly the speed of light for kpc distances. Extragalactic jets, as well as their galactic superluminal counterparts, may well carry more power than what is emitted by their accretion disk. Despite the prediction that jet carry plasma in relativistic motion dates back to 1966 (Rees, 1966), and intense studies over the last 20 years (Begelman, Blandford & Rees, 1984), quantitative estimates of the amount of power that jets can transport have been done only relatively recently, following new observational results. The main difficulty for a quantitative analysis is that the amount of observed power emitted by jets is strongly modified by relativistic aberration, time contraction and blueshift, all dependent on the unknown plasma bulk velocity and viewing angle. The other fundamental unknown is the matter content of jets: we still do not know for sure if they are made by electron–positron pairs or normal electron–proton plasma.

However, there have been many attempts to calculate the power of jets, both in the form of bulk kinetic power and in intrinsic emitted luminosity. In this paper I will summarize some of the recent studies aiming to know the power of jets, and to put some constraints on the jet content. Although I will focus mainly on AGN jets, many of the arguments presented below can be applied both to extragalactic as well galactic superluminal jets, which will be briefly reviewed in the end.

1
2. The lobes of strong extragalactic radio sources

The fact that the lobes of strong radio sources contain a huge amount of energy was known for many years, but Rawlings and Saunders (1991) put the accent on the *power* that the lobes require to exist at all. Their argument is conceptually simple, since they derive the power dividing the total energy by the lobe life timescale. This is the power that jets must supply. This important result depends upon the assumption of equipartition between particles and magnetic field in the lobes, while the life timescale was derived with spectral aging of the observed synchrotron emission and/or by dynamical arguments. When both estimates were possible, they were found to agree. In addition, they found that the derived power correlates with the amount of luminosity observed in the narrow emission lines, which are another isotropic indicator of power, but probably coming from a different origin. The found correlation (once both low and high luminosity objects are included) spans more than 4 decades of power on both axis, and it is more informative than the previously found correlation between the lobe radio power and the narrow line luminosity. This is because only a small fraction of the power received by the lobes may be dissipated into radiation.

3. The jet at VLBI scale

Interferometry can sample sizes of a few pc for objects located at a redshift $z = 1$. This has allowed us to discover superluminal motions of knots in the jets, the main proof of relativistic bulk motion. Radio size and flux constrain the beaming factor of the radio emission, in order not to exceed, by the inverse Compton process, the observed amount of X–rays. If we then restrict ourselves to blazars, believed to be seen at small viewing angles, we can estimate the bulk Lorentz factor $\Gamma$, or directly estimate it and the viewing angle by adding the information of the apparent velocity $\beta_{app}$. The main uncertainties in these estimates are the size of the sources, often at the limit of the instruments, and the Hubble constant ($\beta_{app} \propto 1/H_0$). Therefore average results, coming from a large sample of objects (Ghisellini et al. 1993) are more reliable than quantities derived for a specific object. If the core radio flux is emitted by the incoherent synchrotron process, we can estimate the magnetic field, and the number density $n$ of the emitting particles, which however depends crucially by the low energy cut–off ($\gamma_{min}$) of their energy distribution, where most of the particles are. Since low energy particles would emit self–absorbed synchrotron emission, $\gamma_{min}$ cannot be estimated by the radio data. Bearing these uncertainties in mind, Celotti & Fabian (1992) calculated the bulk motion kinetic power of the jet at VLBI scales:

$$L_{k, VLBI} = \pi R_{VLBI}^2 \beta n' m_e c^3 (\gamma > + a m_p / m_e)$$

where $n' = n / \Gamma$ is the intrinsic density of particles, which have a mean energy $\gamma > m_e c^2$. $a$ measures the amount of protons per electron ($a = 1$ corresponds to equal number of protons and electrons). Protons are assumed to be cold. The calculated $L_k$ was found to match the lobe power if: i) the jet is composed by pairs, with $\gamma_{min} \sim 1$; or ii) the jet is made by protons and electrons, but in this case $\gamma_{min} \sim 30–100$. Celotti & Fabian (1992) preferred the latter solution, since otherwise the required density of pairs, extrapolated from the VLBI scale
back to the initial part of the jet cannot survive against annihilation (Ghisellini et al. 1992). Note that a low energy cut–off of the same order (in the case of proton–electron plasma) is required for polarized sources, to limit the amount of Faraday depolarization. Another important result is that there must be a little amount of thermal particles, since they would increase too much both the bulk kinetic power and the Faraday depolarization (Wardle 1977).

4. Jet power vs accretion disk luminosity

The kinetic power of jets can be best estimated for blazars, since for these sources is much easier to limit the bulk Lorentz factor. On the other hand in these sources the beamed continuum hides the isotropic continuum component at all frequencies but the radio ones. Comparing the bulk kinetic power with the nuclear luminosity produced by accretion is therefore difficult. One way out is to use emission lines, assuming that they reprocess a relatively fixed fraction of the ionizing accretion disk luminosity. In this way Rawlings and Saunders (1991) found $< L_{NLR}/L_{lobes} > \sim 0.01$, while Celotti, Padovani & Ghisellini (1997) found $< L_{BLR}/L_{k,V,LB1} > \sim 0.1$. NLR and BLR stand for narrow and broad emission line regions, respectively. Note that BL Lac objects, lacking emission lines, do not obey these correlations (but FR I radio sources do, Rawlings & Saunders 1991).
Since $L_{NLR} \sim 0.1 L_{BLR} \sim 0.1 L_{\text{ioniz}} \sim L_{\text{disk}}$ and since $L_{k,VLBI} \sim L_{\text{lobe}} \sim L_{\text{jet}}$ we arrive at the very important conclusion that

$$L_{\text{jet}} \sim L_{\text{disk}}$$

(2)

Alternatively, one may assume that a significant fraction of the line regions is illuminated by the beamed jet emission, providing a link between bulk motion power and line luminosity. But in this case steep radio sources should have optical spectra with huge line equivalent widths (these objects are seen at large viewing angles, and the non-thermal continuum is depressed), contrary to what we observe.

We do not know yet the mechanism responsible for the formation and the acceleration of jets. Early attempts to use the strong radiation pressure of the accretion disk failed, due to the strong Compton drag that the moving plasma suffers even at modest speeds. An attractive idea, but not yet explored in detail, is the Blandford & Znajek (1977) process, in which the magnetic field can extract the rotational energy of a Kerr black hole:

$$L_{\text{rot}} \sim 10^{45} \left(\frac{a}{m}\right)^2 M_8^2 B_4^2 \text{ erg s}^{-1} \sim \left(\frac{a}{m}\right)^2 (3R_s)^2 U_{Bc}$$

(3)

where the magnetic field $B = 10^4 B_4$ Gauss, $U_B = B^2/(8\pi)$, the black hole mass $M = 10^8 M_8$ solar masses, $R_s$ is the Schwarzschild radius and $(a/m)$ is the specific black hole angular momentum ($\sim 1$ for maximally rotating black holes). The accretion disk luminosity can be written as

$$L_{\text{disk}} = \pi(3R_s)^2 U_r c$$

(4)

where $U_r$ is the energy density of the radiation produced by the disk. For $U_B = U_r$ we have $L_{\text{disk}} \sim L_{\text{rot}}$ (Celotti et al. 1997). These very simple estimates may be a coincidence, or may testify the crucial role of the magnetic field on AGNs, responsible for both transforming gravitational energy into radiation in the disk and by extracting rotational energy from the black hole.

4.1. Outflowing mass

The jet and the accretion powers can be expressed as

$$L_k = \Gamma \dot{M}_{\text{out}} c^2; \quad L_{\text{disk}} = \eta \dot{M}_{\text{in}} c^2$$

(5)

where $\dot{M}_{\text{in}}$ is the mass accretion rate, and $\eta$ is the efficiency of mass to energy conversion for accretion. Therefore we have

$$\dot{M}_{\text{out}} = \frac{\eta}{\Gamma} \frac{L_k}{L_{\text{disk}}} \dot{M}_{\text{in}} \sim 0.01 \dot{M}_{\text{in}}$$

(6)

The outflowing mass is then a small fraction of the accreted one, but it still corresponds to $\sim 0.1$ solar masses per year for the most powerful blazars.
5. The $\gamma$–ray zone

The discovery that blazars emit a significant (and dominant, during flares) fraction of their power in the $\gamma$–ray band poses important constraints on the part of jet responsible for this emission.

- The overall spectral energy distribution (SED) of blazars consists of two broad peaks, one at frequencies between the IR and the soft X–rays and the other one between the MeV and the GeV band. Due to the limited EGRET sensitivity, we probably detect sources in the $\gamma$–ray band when they flare, but a couple of blazars (3C 279 and PKS 0528+134) were always detected when observed. They suggest that the $\gamma$–ray power is of the same order than the power in the low energy peak during quiescent states, and can be 10 or 100 times larger during flares.

- The $\gamma$–ray flux varies rapidly. EGRET, onboard CGRO, detected variations of a factor 2 in timescales of days. Ground based Cerenkov telescopes have observed factor 2 flux variations in a timescale as short as 20 minutes in Mkn 421 (Gaidos et al. 1996). When possible, variations in the $\gamma$–ray band were observed to be accompanied by variations in other frequency bands, (Maraschi et al. 1994; Hartman et al. 1996; Bloom et al. 1997; Wehrle et al. 1998; Buckley et al. 1996; Macomb et al. 1995).

These potentially very important observations for constraining the different emission models suggest that the bulk of the emission, both in the low energy peak, produced by synchrotron, and in the high energy peak,
presumably produced by inverse Compton, are cospatial and produced by the same electrons.

- If the X and the $\gamma$–ray emission are cospatial, then the very fact to observe $\gamma$–rays implies bulk motion, to evade the limit posed by the $\gamma\gamma \rightarrow e^\pm$ process. In fact this process depends of the compactness of the sources, which is the intrinsic luminosity over size ratio. Radiation must be beamed, in order to derive an intrinsic compactness lower enough to let the source be transparent to $\gamma$–rays. Lower limits to the beaming factors are consistent with those derived by superluminal motion and the requirement not to overproduce X–rays (Dondi & Ghisellini 1995). These limits are particularly severe for TeV sources, since the optical depth for $\gamma\gamma$ collisions increases with energy (for instance $\delta \sim 8\text{–}10$ for Mkn 421), contrary to the old idea that X–ray selected BL Lacs have smaller beaming factors, being seen at larger viewing angles (Maraschi et al. 1986).

- The above point constrains the location of the emitting region. It must be at some distance from any important source of X–rays, which would otherwise absorb the observed $\gamma$–rays. The idea that $\gamma$–rays are produced all along the jet, and that only those produced at larger distances survive and arrive to us (Blandford & Levinson 1994) must face the problem of reprocessing: if a significant fraction of the power emitted in the inner part of the jet in $\gamma$–rays get absorbed, the created pairs, born relativistic in a dense photon environment, emit X–rays by Compton scattering UV accretion disk photons, and inevitably the power originally in the $\gamma$–ray band gets reprocessed into the X–ray band (Ghisellini & Madau 1996). The observed X–ray and $\gamma$–ray luminosities should therefore be roughly equal, contrary to what observed. There must be a mechanism able to transport energy from the central powerhouse to a few hundreds Schwarzschild radii without dissipating it.

- The $\gamma$–ray emitting zone is where most of the power is radiated away. Models interpreting the overall emission of blazars can take advantage of that, and assume an homogeneous region, rather than a many–parameter inhomogeneous jet. The location of the emitting region is constrained on one side by the requirement of $\gamma\gamma$ transparency, and on the other side by the rapid variability: therefore it must be at some $10^{17}$ cm from the black hole, and have a dimension of $\sim 1/\Gamma$ times smaller.

- It is interesting to compare, for this region, the power that it must be transported in the form of bulk kinetic motion of the plasma and the power in the form of radiation. To this end, one needs to estimate the intrinsic parameters of the source, such as the value of the magnetic field, the particle density, and the matter composition. This has been done by Ghisellini et al. (1998) for all EGRET detected sources. Note that these fits provide useful constraints for classes of sources, rather than for specific objects, since the radio to $\gamma$–ray data are very rarely taken simultaneously, and since for few sources we have a very good spectral coverage.
6. The power of jets at the 0.1 pc scale

Eq. (1), once $R_{VLBI}$ is replaced by the dimension estimated by model fitting and by the variability timescale, measures the bulk kinetic power of the jets at the 0.1 pc scale. There is however another form of power: the Poynting flux:

$$L_B = \pi R^2 T^2 U_B c$$

(7)

where $U_B$ is the intrinsic (comoving) magnetic energy density. The observed synchrotron luminosity $L_{s,obs}$ is derived, assuming isotropy, by multiplying the observed flux by $4\pi d_L^2$, where $d_L$ is the luminosity distance. Then $L_{s,obs} = \delta^4 L'_s$. Instead, the total synchrotron power received on the entire solid angle is $L_{s,tot} = \delta^2 L'_s$. For a blob of dimension $R$ we have

$$L_{s,obs} = \delta^4 Vol \int n'(\gamma)\gamma^s m_e c^2 d\gamma = \frac{16\pi R^3}{9} \delta^4 \sigma_T cn' U_B < \gamma^2 >$$

(8)

where $<\gamma^2>$ is averaged over the emitting particle distribution. By substituting the particle density derived by this equation into Eq. (1), and assuming $\delta = 1$ we have

$$L_k = \frac{9\pi m_e c^2}{2\sigma_T} \frac{L_{s,obs}}{R\Gamma B^2} < \gamma > \frac{+m_p/m_e}{<\gamma^2>}$$

(9)

We see that $L_k \propto (B\Gamma)^{-2}$, while $L_B \propto (B\Gamma)^2$: therefore $L_{jet} \equiv L_k + L_B$ is minimized for some value of $B\Gamma$, which corresponds to equipartition between particle and magnetic energy densities. In this case the observed (at a viewing angle $\sim 1/\Gamma$) synchrotron emission is maximized. EGRET sources obey this condition if $\gamma_{min}$ (entering in the definition of $<\gamma>$ and $<\gamma^2>$) is again of the order of $\sim 30$ and if electron-positron pairs are not dynamically important. In addition, for this value of $\gamma_{min}$ we find particle conservation between the $\gamma$-ray and the VLBI emitting zones of the jet.

6.1. Meaning of equipartition of power

We are used to the equipartition argument regarding particle and magnetic energy. In the previous section we have instead applied the similar, but conceptually different concept of equipartition of particle bulk motion power and Poynting flux. The synchrotron power then relates the two. We are then comparing the velocity at which particle bulk kinetic and magnetic energies are converted into radiation. With the assumption that the viewing angle is $1/\Gamma$ we have that for a given observed synchrotron power, equipartition between $L_k$ and $L_B$ corresponds to the minimum $L_{jet} = L_k + L_B$. Alternatively, for a given $L_{jet}$, equipartition between $L_k$ and $L_B$ ensures that we observe the maximum possible synchrotron power (at $1/\Gamma$).

Assuming steady state, we also have that the observed luminosity $L_{r,obs}$ (i.e. the sum of the synchrotron and the Compton luminosities) integrated over the solid angle, cannot be greater than $L_{jet}$, i.e. $\Gamma^2 L'_r = L_{r,obs}/\Gamma^2 \leq L_{jet}$. Since $L'_r$ depends on $<\gamma^2>$ which in turn is a function of $\gamma_{max}$, we can limit $\gamma_{max}$ for a given magnetic field and particle density (i.e. for a given $L_{jet}$).
Figure 3. The power of jets, in the form of radiation, bulk motion and Poynting flux, as a function of bulk Lorentz factor. Upper panel: $R = 5 \times 10^{16}$ cm, $B = 3$ Gauss, $L_{s, \text{obs}} = 10^{47}$ erg s$^{-1}$, $L_{r, \text{obs}} = 10^{48}$ erg s$^{-1}$, $(\langle \gamma \rangle + m_p/m_e)/\langle \gamma^2 \rangle = 1$. Mid panel: $R = 5 \times 10^{16}$ cm, $B = 1$ Gauss, $L_{s, \text{obs}} = 5 \times 10^{46}$ erg s$^{-1}$, $L_{r, \text{obs}} = 10^{47}$ erg s$^{-1}$, $(\langle \gamma \rangle + m_p/m_e)/\langle \gamma^2 \rangle = 10^{-2}$. Bottom panel: $R = 10^{16}$ cm, $B = 1$ Gauss, $L_{s, \text{obs}} = 2 \times 10^{46}$ erg s$^{-1}$, $L_{r, \text{obs}} = 3 \times 10^{46}$ erg s$^{-1}$, $(\langle \gamma \rangle + m_p/m_e)/\langle \gamma^2 \rangle = 10^{-3}$. These parameters have been used after the fits to all EGRET blazars, presented in Ghisellini et al. (1998) (upper two panels) and the model used in Pian et al. (1998) for the flaring state of Mkn 501 of April 1997. Note that for these parameters the bulk kinetic power and the Poynting flux power are approximately equal for $\Gamma \sim 10-15$, which is the value used for the fits. This strongly suggests that blazars jets are in equipartition. From Ghisellini & Celotti (1998).
It is intriguing to interpret the Mkn 501 flare of April 1997, when BeppoSAX observed the peak of the synchrotron spectrum at 100 keV, by assuming that the available jet power was the same as in the quiescent state, while the efficiency of the radiative power to tap the available energy increased because $\gamma_{max} \propto < \gamma^2 >$ increased. From Fig. 3 we then have that Mkn 501 was using, during the flare, the entire jet power. A further increase in $\gamma_{max}$ was therefore not possible, since it would have resulted in $L'_r \Gamma^2 > L_{jet}$.

Should other sources exist with even higher $\gamma_{max}$ than Mkn 501 during flares? The answer is yes, provided that the power balance is not violated:

$$\Gamma^2 L'_s < \Gamma^2 L'_r < L_{jet} \rightarrow < \gamma^2 > \frac{< \gamma >}{m_p/m_e} \frac{9\pi \Gamma^2 R_m c^3}{128} \frac{1}{\sigma_T L_B}$$ (10)

We see that larger values of $\gamma_{max} \propto < \gamma^2 >$ are possible for smaller $L_B \sim L_{jet} \propto L_{s,obs}$. This can be understood in this way: the cooling rate for electrons of the highest energies is proportional to $\gamma_{max}^2 U_B$. At the limit this quantity is fixed by the total amount of power that can be emitted. Therefore $\gamma_{max} \propto 1/U_B \propto 1/L_B \propto 1/L_{s,obs}$. It is then no coincidence that the 3 already known TeV sources are three nearby, low luminosity BL Lacs. More extreme sources (with larger $\gamma_{max}$) should be even less powerful, and weak TeV emitters, since the Klein Nishina decline of the cross section becomes increasingly effective as $\gamma_{max}$ increases.

7. Matter content of AGN inner jets

To summarize the findings about the power in bulk motion of AGN jets:

- There are different ways to measure the jet power. One is to divide the energy content of the lobes by their life-time. Another is to estimate the size, the particle density and the bulk Lorentz factor at different locations in the jet. The main uncertainty is to correctly calculate the particle density, which depends on the low energy cut-off of their energy distribution, not directly observable. However, by assuming $\gamma_{min} \sim 30$ and a proton–electron jet, the bulk motion jet power both at the VLBI scale and at the $\gamma$–ray emitting region scale are of the same order of the power required by the lobes to exist.

- The jet power is also of the same order than the power in the radiation emitted by the accretion disk, illuminating the line emitting regions. This may indicate the key role played by the magnetic field both in extracting the gravitational energy of the accretion disk and the rotational energy of the black hole.

- Blazars work nearly at equipartition of powers. This means that that they are very efficient synchrotron radiators. The method of minimizing the sum of the bulk motion power in particles, in Poynting flux and emitted radiation gives a particular value of $\Gamma B$. More importantly, we can set a lower limit to the jet power of AGNs.
With these informations we can try to work out some constraints on the matter content of the inner part of jets, and the main carriers of the jet power. Previous reviews on this subject are by Celotti (1997, 1998), and by Celotti & Ghisellini (1998, in preparation).

Let assume that the central powerhouse has to produce a jet power \( L_{\text{jet}} = 10^{46} L_{\text{jet,46}} \) erg s\(^{-1}\), and let us consider different possibilities of the composition of jets at a distance \( z = 10^{15} z_{15} \) cm from the black hole, and assume there a cross section \( R = 10^{14} R_{14} \) cm of the jet. The bulk Lorentz factor is \( \Gamma = 10 \Gamma_{1} \).

- **Cold electron–positron pairs**
  
  We can estimate how many pairs we need to carry \( L_{\text{jet}} \), and their corresponding scattering optical depth \( \tau_{\pm} \equiv \sigma_{T} n R \), where \( n' = n / \Gamma \):

  \[
  \tau_{\pm} \sim 86 \frac{L_{\text{jet,46}}}{R_{14} \Gamma_{1}} \tag{11}
  \]

  With such a large optical depth, the pairs annihilate in a timescale \( \sim R/(c \tau_{\pm}) \ll R/c \), and the entire \( L_{\text{jet}} \) is transformed in a beamed annihilation line. While annihilating, pairs will also scatter ambient photons, mainly the UV produced in the inner accretion disk, producing, by bulk Compton, a feature at \( \sim \Gamma_{2}^{2} 1 \) keV, of huge luminosity, never observed. We conclude that cold pairs cannot be dynamically important.

- **Hot electron–positron pairs**
  
  If pairs are hot, with an average energy \( < \gamma > \sim m_{e} c^{2} \), their annihilation cross section is smaller, and fewer of them are required to carry \( L_{\text{jet}} \). But in this case a severe limit comes from the Compton emission they would produce. Their Comptonization parameter \( y \) is (assuming \( \tau_{\pm} < 1 \))

  \[
  y_{\pm} \equiv \tau_{\pm} \Gamma^{2} < \gamma^{2} > \sim 8.6 \times 10^{3} \frac{\Gamma_{1} < \gamma^{2} >}{R_{14} < \gamma >} \tag{12}
  \]

  which is huge. The cooling lifetime of these pairs is very short, resulting again in a very rapid transformation of the entire \( L_{\text{jet}} \) into Compton radiation. Therefore even hot pairs cannot be dynamically important.

- **Cold Protons**
  
  The scattering optical depth \( \tau_{p} \) of the associated electrons is a factor \( m_{p}/m_{e} \) smaller, and the corresponding \( y \) parameter, assuming that these electrons are cold, is

  \[
  y \sim 5 \frac{\Gamma_{1} L_{\text{jet,46}}}{R_{14}} \tag{13}
  \]

  Bulk Compton radiation (see Sikora et al. 1997) should therefore be important, but the details of this signature have still to be worked out, especially in the case of accelerating plasma. A detection of a feature resembling a ‘line’ at \( \nu \sim \Gamma^{2} \nu_{UV} \sim \Gamma_{2}^{2} \) keV would be extremely important, revealing both the value of the terminal Lorentz factor, the value of \( L_{\text{jet}} \) and the fact that already in the
inner regions the jet power is transported in the form of cold protons. It may be possible that the recently detected ∼1 kev feature in PKS 0637–752 (Yakoob et al. 1998) is just this ‘line’.

- **Hot Protons**

If the protons have a mean Lorentz factor $< \gamma_p >$, we need a factor $1/ < \gamma_p >$ less protons to carry $L_{jet}$, thus lowering the $y$ parameter by the same amount. On the other hand, the value of the magnetic field necessary to confine them is large, comparable to the one necessary to transport $L_{jet}$ in the form of a Poynting flux, see below.

- **Poynting flux**

The value of the magnetic field corresponding to $L_{jet} \sim L_B$ is

$$B \sim 2 \times 10^3 \frac{L_{jet,46}^{1/2}}{\Gamma_1 R_{14}}$$

which is approximately the same value of the magnetic field derived by $U_B \sim U_{r,disk}$ assuming $L_{disk} \sim L_{jet}$.

From the above simple estimates we conclude that, initially, $L_{jet}$ can be in the form of a Poynting flux, gradually accelerating matter until equipartition is reached, as pointed out in the studies of Li, Chiueh & Begelman (1992) and Begelman & Li (1994).

8. **Galactic superluminals**

GRS 1915+105 and J1655–40 showed superluminal motion of both approaching and receding blobs in radio interferometry observations (Mirabel & Rodriguez, 1994; Tingay et al. 1995; Hjellming & Rupen 1995). This allowed the determination of both the value of the true velocity ($\beta = 0.92$ for both, corresponding to $\Gamma = 2.55$) and the viewing angle ($\theta \sim 70^\circ$ for GRS 1915+105 and slightly more for J1655–40). Their vicinity make it possible to detect their proper motion with VLA, at sub-arcsecond resolution. In Fig. 4 we present the SED of the two sources, from a collection of data (of different epochs) taken from the literature.

The extremely complex variability of the X–ray emission is currently monitored by RXTE, and is the subject of intense studies. As Belloni et al. (1997) suggested, the X–ray data may indicate phases of accretion disk disruption and subsequent ‘re–filling’, also suggested by combined multiband optical and X–ray observations in J1655–40 (Orosz et al. 1997).

We can repeat for GRS 1915+105 the same arguments we used for AGN, trying to constrain the kinetic bulk power of its jets. Assuming a size of $R = 7 \times 10^{15}$ cm emitting a synchrotron observed luminosity of $L_{syn,obs} = 10^{33}$ erg s$^{-1}$, Gliozzi et al. (1998) derived, by the same method outlined in §6, a minimum jet power of $L_{jet,min} \sim 10^{40}$ erg s$^{-1}$ for a low energy cut–off in the electron distribution of $\gamma_{min} = 10$, and assuming an electron–proton jet (these authors discuss and reject the possibility of a jet made by electron–positron pairs). Since in this case we know the bulk Lorentz factor and the viewing angle, we also know
Figure 4. The SED of GRS 1915+105 and J1655–40 constructed using non–simultaneous data, taken from the literature. Note, for 1915+105, the $6\sigma$ TeV value, obtained by HEGRA, and reported in Aharonian & Heinzelmann (1997). Dashed lines corresponds to the probable spectrum of the companion star of 1655–40 and to a multi–color blackbody spectrum, to represent its accretion disk emission.

Figure 5. The bulk motion power, the power in Poynting flux and their sum as a function of the magnetic field for GRS 1915+105. The adopted observed synchrotron luminosity corresponds to the radio power of the April 1994 flare event. It is assumed that the electron distribution is a power law, $\propto \gamma^{-2}$ extending from $\gamma_{\text{min}}$ to $\gamma_{\text{max}} = 10^3$. 

$\gamma_{\text{min}} = 1$, $\gamma_{\text{max}} = 10^3$; $L_{\text{syn}} = 10^{33}$ erg s$^{-1}$.
the beaming factor, and the minimization of the total jet power is for a particular value of the magnetic field $B$, as illustrated in Fig. 5.

9. Matter content of galactic superluminal jets

The very large bulk kinetic power derived for GRS 1915+105 exceeds the power observed in X–rays, presumably produced in the accretion disk, by a factor of a few. We then derive

$$\dot{M}_{out} = 0.5 \left( \frac{\eta}{0.1} \right) \left( \frac{2.55}{\Gamma} \right) \left( \frac{L_k}{10^{40} \text{ erg s}^{-1}} \right) \left( \frac{10^{39} \text{ erg s}^{-1}}{L_{disk}} \right) \dot{M}_{in}$$

(15)

This suggests that, if the jet material comes from the accretion disk, it is a significant fraction of mass inflow rate, possibly corresponding to ‘traumatic’ disk changes. On the other hand, it may well be that the above equations flags the need for lower efficiencies $\eta$, to reduce the ratio $\dot{M}_{out}/\dot{M}_{in}$ to the 1 per cent level, as in AGN.

We can here repeat the arguments discussed in §7 for the matter content in the jets of GRS 1915+105, keeping in mind that in this case we know $\Gamma$ and the viewing angle, corresponding to a beaming factor $\delta \sim 0.5$. A more detailed discussion can be found in Gliozzi et al. (1998).

$e^\pm$ pairs — If the jet is made by pairs at its start, their density correspond to a very large scattering optical depth $[\tau_{e^\pm} \sim 10^3 L_{k,40}/(\Gamma R_7)]$, and they cannot survive annihilation. If the pairs are hot, with an average energy $< \gamma > m_e c^2$ at the start of the jet, where they are embedded in a dense radiation field, they cool very rapidly, converting a large fraction of $L_k$ into radiation. Then a pure pair plasma, neither cold or hot, can carry the kinetic power.

Electron – proton plasma — If the jet is composed, initially, by cold protons and hot electrons, with mean energy $< \gamma > m_e > m_p$, we have the same case as above: the electrons rapidly cool.

There are no severe limits, instead, if both electrons and protons are cold. The initial scattering optical depth is a few, and the bulk Compton emission in our direction is at frequencies where the flux is dominated by the radiation produced by the accretion disk.

If the protons are hot, the magnetic field needed to confine them has a value of the same order than the magnetic field required to transport $L_{jet}$ in the form of a Poynting vector.

Poynting vector — The magnetic field needed to carry $L_{jet}$ has a value

$$B \sim 3 \times 10^8 \frac{L_{jet,40}^{1/2}}{R_7} \text{ Gauss}$$

(16)

This is also approximately the value needed to the Blandford–Znajek mechanism to extract $10^{40} \text{ erg s}^{-1}$ from a maximally spinning black hole of 10 solar masses.
10. Conclusions

We are starting to tackle the very important problem of how jets are formed and accelerated by deriving their energetics and matter content in different places along the jet and on the extended, isotropic lobes.

This was possible on one hand by having a sizeable sample of sources observed with VLBI, and for which we know their apparent speeds, and on the other hand by the discovery of $\gamma$–ray emission of blazars, fixing the energetics of the observed radiation. An important improvement in our knowledge would come from observing features in the spectra of jet sources, originating in the moving plasma, and flagging its bulk velocity. One of them could be the bulk Compton ‘line’ at $\sim$1keV discussed by Sikora et al. (1997). Other feature could be present, if the relativistic plasma coexists with small blobs of cold materials, as suggested by Celotti et al. (1998), and Celotti (1998, these proceedings). Large area X–ray detectors, such as XMM and Constellation–X, are probably the best instruments to find these important clues.

On a parallel path, the discovery of galactic superluminal sources allows us to study nearby (bright) objects whose timescales, scaling with the black hole mass, are a factor $\sim 10^8$ smaller than what we observe in AGNs: a day in the lifetime of GRS 1915+105 corresponds to $\sim 3 \times 10^5$ years of a powerful blazar. These ‘lab’ systems will hopefully help us to understand the jet phenomenon, and the strong gravity physics behind it.

Acknowledgments. It is a pleasure to thank Annalisa Celotti for years of discussions and fruitful collaboration, and in particular for this review, largely based on the very intense brainstorm we had in Graftavallen.

References

Aharonian F. & Heinzelmann G., 1997, astro-ph/9702059
Begelman M.C. & Li Z.-Y., 1994, ApJ, 426, 269
Begelman M.C., Blandford R.D. & Rees M.J., 1984, Rev. Mod. Phys., 56, 255
Belloni T., Mendez M., King A.R., van der Klis M. & van Paradijs J., 1997, ApJ 479, 145
Blandford R.D. & Znajek R.L., 1977, MNRAS, 176, 465
Bloom S.D. et al. 1997, ApJ, 490, L145
Buckley J.H. et al., 1996, ApJ 472, L9
Celotti A., 1997, in Relativistic jets in AGNs, eds. M. Ostrowski, M. Sikora, G. Madejski & M. Begelman, p. 270
Celotti A., 1998, in Astrophysical jets: open problems, (Gordon & Breach Science publ.), eds. S. Massaglia & G. Bodo (Amsterdam), p. 79
Celotti A. & Fabian A.C. 1993, MNRAS, 264, 228
Celotti A., Kuncic Z., Rees M.J. & Wardle J.F.C. 1998, MNRAS, 293, 288
Celotti A., Padovani P. & Ghisellini G., 1997, MNRAS, 286, 415
Dondi L. & Ghisellini G., 1995, MNRAS, 273, 583
Gaidos J.A. et al., 1996, Nature, 383, 319
Ghisellini G., Celotti A., Fossati G., Maraschi L. & Maraschi L., 1998, MNRAS, in press, astro-ph/9807317
Ghisellini G. & Madau P., 1996, MNRAS, 280, 67
Ghisellini G. & Celotti A., 1998, submitted to MNRAS
Ghisellini G., Padovani P., Celotti A. & Maraschi L., 1993, ApJ, 407, 65
Ghisellini G., Celotti A., George I.M. & Fabian A.C., 1992, MNRAS, 258, 776
Gliozzi M., Bodo G. & Ghisellini G., 1998, MNRAS, in press
Hartman, R.C. et al., 1996, ApJ, 461, 698
Hjellming R.M. & Rupen M.P., 1995, Nature, 365, 464
Li Z.-Y., Chiueh T. & Begelman M.C., 1992, ApJ, 394, 459
Macomb D.J. et al. 1995, ApJ, 449, L99
Maraschi L., Ghisellini G., Tanzi E.G. & Treves A., 1986, ApJ, 310, 325
Maraschi L., et al., 1994, ApJ, 435, L91
Mirabel I.F. & Rodriguez L.F., 1994, Nature, 371, 46
Orosz J.A., Remillard R.A., Bailyn C.D. & McClintock J.E., 1997, ApJ, 478, L83
Pian E. et al., 1998, ApJ, 491, L17
Rawlings S.G. & Saunders R.D.E., 1991, Nature, 349, 138
Rees M.J., 1996, Nature, 211, 468
Sambruna R.M. et al., 1998, submitted to ApJ
Sikora M., Madejski G., Medderski R. & Poutanen J., 1997, ApJ, 484, 108
Tingay S.J. et al., 1995 Nature, 374, 141
Yakoob T., George I.M., Turner T.J., Nandra K., Ptak A. & Serlemitsos P.J., 1998, ApJ, in press (astro-ph/9807349)
Wardle, J.F.C., 1977, Nature, 269, 563
Wehrle A.E. et al., 1998, ApJ, 497, 178