THE ASTROPHYSICAL JOURNAL, 464:L67–L70, 1996 June 10

THE NUCLEAR JET IN M81

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Received 1996 February 1; accepted 1996 April 1

ABSTRACT

In this Letter we apply the jet-disk symbiosis model developed for Sagittarius A* to M81*—the nucleus of the nearby galaxy M81. The model accurately predicts the radio flux and size of M81* for the observed bolometric luminosity of the nuclear source, with no major free parameter except for the inclination angle. We point out that the usually applied, free conical jet emission model implies a longitudinal pressure gradient that must lead to a moderate acceleration of the jet along its flow direction. This usually neglected, gradual acceleration naturally accounts for the inverted spectrum and the size-frequency relation of M81*, and may be a general feature of radio cores. So far, M81* is the best case for a radio-loud jet nature of the compact radio core in the nucleus of a spiral galaxy. The fact that one can account for Sgr A* and M81* with the same model by simply changing the accretion rate strongly supports the jet-disk symbiosis model as an explanation for the compact radio cores of galaxies in general.

Subject headings: accretion, accretion disks — black hole physics — Galaxy: center — galaxies: active — galaxies: individual (M81) — galaxies: jets

1. INTRODUCTION

Quite a few nearby galaxies seem to have compact radio cores in their nuclei; prominent cases are the Milky Way (Sagittarius A*), M31, and M81. Those radio cores resemble the cores of radio-loud quasars, showing a very high brightness temperature and a flat-to-inverted radio spectrum that extends up to submillimeter wavelengths. Several models have been developed to explain those cores in the context of black hole accretion: Melia (1992a, 1992b) suggested a spherical accretion model for Sgr A* and, what he called, M31*. Falcke et al. (1993a) and Falcke, Mannheim, & Biermann (1993b, hereafter FMB93) proposed an alternative model, where Sgr A* was explained as the core of a radio jet, fed by an underluminous, starving accretion disk (see also Falcke 1996a for a review, and Falcke & Heinrich 1994 for M31*). This model evolved into the jet-disk symbiosis approach (Falcke & Biermann 1995, hereafter FB95; Falcke 1996b) that unified the explanation for radio cores of quasars (Falcke, Malkan, & Biermann 1995, hereafter FMB95), Galactic jet sources (Falcke & Biermann 1996), and Sgr A* into a single picture. The basic idea was to postulate that black holes, jets, and disks form closely coupled systems with little variations from one system to another, except for the accretion rate.

Recent VLBI (Bietenholz et al. 1996), multiwavelength (Ho, Filipenko, & Sargent 1996), and submillimeter observations (Reuter & Lesch 1996) have now shown that the radio core in M81—which, analogous to Sgr A* and M31*, we will label M81* hereafter—is very similar to Sgr A*. This wealth of data now makes M81* an excellent laboratory to test the jet-disk symbiosis in detail.

2. FREE JET WITH PRESSURE GRADIENT

One of the interesting findings of the VLBI observations (de Bruyn et al. 1976; Bartel et al. 1982; Bietenholz et al. 1996) is that the radio core of M81* is elongated and its size is intrinsically frequency dependent with $r \propto \nu^{-0.8\pm0.05}$. A frequency-dependent size was one of the basic predictions of the jet model and excludes any homogenous, optically thin models (e.g., as in Duschl & Lesch 1994). However, the measured size-frequency relation is slightly shallower than in the Blandford & Königl (1979, hereafter BK79) free jet model adopted by FB95, and the radio spectra of Sgr A* and M81* are both slightly inverted rather than flat, as in the simple model. Here we show that a self-consistent treatment of the BK79 model implies a weak acceleration of the bulk jet flow due to its longitudinal pressure gradient, which can naturally explain the observed size and spectral indices in compact radio cores.

2.1. *Longitudinal Velocity Profile*

As in FB95, we shall describe the jet core within the framework of the relativistic gasdynamics of a relativistic gas with adiabatic index $\Gamma = 4/3$. We consider only the supersonic regime and impose, as a boundary condition, that the jet expands freely with its initial sound speed β_s without any lateral gradients behind the jet nozzle. This leads to the familiar conical jet with $B^2/4\pi \propto r^{-2}$ (BK79), where adiabatic losses due to lateral expansion need not be considered. For a confined jet scenario (e.g., Sanders 1983) at larger scales, however, the adiabatic losses could be quite severe, with energy densities scaling as $r^{-2\Gamma}$.

Nonetheless, even in a simple free jet, at least some work due to expansion will be done, because there is always a longitudinal pressure gradient, which will accelerate the jet along its axis. This acceleration of the jet flow is described by the z-component of the modified, relativistic Euler equation (e.g., Pomraning 1973, eq. 9.171) in cylindrical coordinates, where we set $\partial/\partial r = 0$ and $\partial/\partial\theta = 0$,

$$\gamma_j \beta_j \frac{\partial}{\partial z}\left(\gamma_j \beta_j \frac{\omega}{n}\right) = -\frac{\partial}{\partial z} P. \tag{1}$$

Here, $\omega = m_p n c^2 + U_j + P_j$ is the enthalpy density of the jet, U_j is the internal energy density, n is the particle density, and $P_j = (\Gamma - 1)U_j$ is the pressure in the jet (all in the local rest frame). For the "maximal jets"—the radiatively most efficient type of jet (FB95)—to be discussed here, we demand the equivalence of internal energy and kinetic (or, better, rest-mass) energy $U_j \simeq m_p nc^2$, hence $\omega = (1+\Gamma)U_j$ and $\omega/n = (1+\Gamma)m_p c^2 =$ const at the sonic point $z = z_0$. In the free jet with conical shape, the energy density evolves as $U_j \propto (\gamma_j \beta_j)^{-\Gamma} z^{-2}$, and we do not consider any loss mechanisms other than adiabatic losses due to the longitudinal expansion. Using the relations mentioned above, the Euler equation then becomes

$$\frac{\partial \gamma_j \beta_j}{\partial z}\left\{\frac{[(\Gamma+\xi)/(\Gamma-1)](\gamma_j\beta_j)^2-\Gamma}{\gamma_j\beta_j}\right\} = \frac{2}{z}, \qquad (2)$$

with $\xi = \{\gamma_j\beta_j/[\Gamma(\Gamma-1)/(\Gamma+1)]\}^{1-\Gamma}$. For $\xi \sim 1$, this is analogous to the Euler equation for the well-known isothermal, pressure driven winds, with the wind speed replaced by the proper jet speed, and the sound speed is constant and fixed by the required equivalence between internal and rest-mass energy density at a value $\beta_s = [(\Gamma-1)/(\Gamma+1)]^{1/2} \sim 0.4$.

The asymptotic solution of equation (2) for $\xi =$ const and $z \to \infty$ is $\gamma_j\beta_j \propto 2(\ln z)^{1/2}$. If we ignore terms of the order $\ln \gamma_j\beta_j$, we could approximate the solution by $\gamma_j\beta_j \simeq \{[(\Gamma-1)/(\Gamma+1)][\Gamma + 4\ln(z/z_0)]\}^{1/2}$. For the following calculations, however, we will use the exact numerical solution to equation (2) ($\xi \neq$ const), but the deviation from the approximate, asymptotic solution is rather small.

2.2. *Plasma Properties*

The basic ideas on how to derive the synchrotron emissivity and the basic properties of a jet in a coupled jet-disk system have been described extensively in FMB93 and FB95. The power $Q_j = q_j \dot{M}_{\rm disk} c^2 = q_{j/l} L_{\rm disk}$ of *one* jet cone is a fixed fraction of the disk luminosity; relativistic particles and the magnetic field B are in equipartition within a factor k_{e+p}, which we hereafter set to 1, and the energy fluxes are conserved along the conical jet (for a moment, we will forget the adiabatic losses). Mass conservation requires that the mass loss in the jet $\dot{M}_{\rm jet}$ is smaller than the mass accretion rate in the disk $\dot{M}_{\rm disk}$, thus $q_m = \dot{M}_{\rm jet}/\dot{M}_{\rm disk} < 1$, while mass and energy of the jet are coupled by the relativistic Bernoulli equation $\gamma_j q_m[1 + \beta_s^2/(\Gamma-1)] = q_j$ (FMB93).

Here we will make use of the same logic and notation, but with three changes in respect to FB95, namely, (1) applying the velocity law in equation (2), (2) neglecting the energy contents in turbulence, and (3) considering only a quasi-monoenergetic energy distribution for the electrons at a Lorentz factor γ_e (usually $\gtrsim$100). The latter is indicated by the steep submillimeter-IR cutoff of Sgr A* (Zylka et al. 1995)—and probably also M81* (Reuter & Lesch 1996)—which is different from typical Blazar spectra and precludes an initial electron power-law distribution (as in FMB93).

The semiopening angle of the jet is $\phi = \arcsin(\gamma_s\beta_s/\gamma_j\beta_j)$, and the magnetic field in the comoving frame of a maximal jet with the given sound speed, $L_{\rm disk} = L_{41.5}10^{41.5}$ ergs s^{-1}, $q_{j/l} = 0.5 q_{0.5}$, and $z_{16} = z/10^{16}$ cm becomes (see eq. [19] in FB95)

$$B = 0.6\ {\rm G}\ \sqrt{\beta_j L_{41.5} q_{0.5}}\, z_{16}^{-1}. \qquad (3)$$

The number of relativistic electrons that are to be in equipartition with the magnetic field are a fraction $x_e = n_e/n$ of the total particle number density, and the energy density ratio between relativistic protons and electrons is $(\mu_{p/e} - 1)$. From the energy equation $\gamma_j \omega \gamma_j \beta_j c \pi r^2 = q_{j/l} L_{\rm disk}$, we find that the characteristic Lorentz factor and electron density required to achieve equipartition are

$$\gamma_e = m/(4\Gamma m_e \mu_{p/e} x_e) = 344/(\mu_{p/e} x_e), \qquad (4)$$

$$n_e = 45\ {\rm cm}^{-3}\ \beta_j L_{41.5} q_{0.5} x_e z_{16}^{-2}. \qquad (5)$$

Finally, to incorporate adiabatic losses, we now have to make the following transitions with respect to the equations in FB95:

$$\gamma_j\beta_j \to \gamma_j\beta_j(z), \quad \gamma_e \to \gamma_e[\gamma_j\beta_j(z)/\gamma_j\beta_j(z_0)]^{1/3},$$
$$B \to B[\gamma_j\beta_j(z)/\gamma_j\beta_j(z_0)]^{1/6}. \qquad (6)$$

2.3. *Synchrotron Emission*

The local spectrum of the jet will be $F_\nu \propto \nu^{1/3}$ between the synchrotron self-absorption frequency $\nu_{\rm ssa}(z)$ and the characteristic frequency $\nu_c(z) = 3e\gamma_e^2 \sin\alpha_e B(z)/4\pi m_e c$ (here we will use an average pitch angle $\alpha_e = 60°$). For the maximal jet using equations (3), (4), (5), and (6), we have in the observers frame

$$\nu_c(z) = 100\ {\rm GHz}\ \mathcal{D}\sqrt{L_{41.5}q_{0.5}}/(\sqrt{\beta_j}\gamma_j x_e^2 \mu_{p/e} z_{16}), \qquad (7)$$

with the Doppler factor $\mathcal{D} = 1/\gamma_j(1-\beta_j\cos i)$ for an inclination i of the jet axis to the line of sight.

To find the local synchrotron self-absorption frequency $\nu_{\rm ssa}$, we have to solve the equation $\tau = n_e \sigma_{\rm sync}(\nu)2r_j/\sin i = 1$ and transform it into the observers frame. The jet radius is $r_j \sim \phi z$, and the synchrotron self-absorption cross section for a monoenergetic electron distribution is given by $\sigma_{\rm sync} = 4.9\times10^{-13}$ cm^2 $(B/{\rm G})^{2/3}\gamma_e^{-5/3}(\nu/{\rm GHz})^{-5/3}$, yielding

$$\nu_{\rm ssa} = 3.3\ {\rm GHz}\ \mathcal{D}\,\frac{\beta_j^{1/5}L_{41.5}^{4/5}q_{0.5}^{4/5}x_e^{8/5}\mu_{p/e}}{\gamma_j^{3/5}(\mathcal{D}\sin i)^{3/5}z_{16}}. \qquad (8)$$

If we now use the velocity profile in equation (2), we can invert equation (7) to find the size of the jet as a function of observed frequency. For the asymptotic regime $z \gg z_0$, ν_c is approximated for a fixed inclination angle to within a few percent by a power law in z, such that

$$z_c = (z_{c,0}/\sin i)(\mu_{p/e}x_e)^{-2\xi}(q_{0.5}L_{41.5})^{\xi/2}z_{13.7}^{1-\xi}\nu_{10.3}^{-\xi}, \qquad (9)$$

where the parameters are $z_{13.7} = z_0/3$ AU, $\nu_{10.3} = \nu/22$ GHz, $\xi = (0.99, 0.95, 0.9, 0.89, 0.88)$, and $z_{c,0} = (500, 1200, 1100, 900, 700)$ AU for $i = (5°, 20°, 40°, 60°, 80°)$.

The total spectrum of the jet is obtained by integrating the synchrotron emissivity $\epsilon_{\rm sync}$ along the jet: $F_\nu = (4\pi D^2)^{-1}\int_{z(\nu_{\rm ssa})}^{z(\nu_c)}\epsilon_{\rm sync}\pi r^2\,dz$, which can again be approximated using power laws:

$$F_\nu = 745\ {\rm mJy}\ (q_{0.5}L_{41.5})^{1.46}\mu_{p/e}^{0.17}x_e^{1.17}z_{13.7}^{0.08}\nu_{10.3}^{0.08}$$
$$-\ 337\ {\rm mJy}\ (q_{0.5}L_{41.5})^{1.54}\mu_{p/e}^{0.92}x_e^{2.1}z_{13.7}^{0.08}\nu_{10.3}^{0.08}, \qquad (10)$$

$$F_\nu = 247\ {\rm mJy}\ (q_{0.5}L_{41.5})^{1.42}\mu_{p/e}^{0.33}x_e^{1.33}z_{13.7}^{0.16}\nu_{10.3}^{0.16}$$
$$-\ 143\ {\rm mJy}\ (q_{0.5}L_{41.5})^{1.48}\mu_{p/e}^{0.85}x_e^{1.95}z_{13.7}^{0.15}\nu_{10.3}^{0.15}, \qquad (11)$$

$$F_\nu = 106\ {\rm mJy}\ (q_{0.5}L_{41.5})^{1.40}\mu_{p/e}^{0.40}x_e^{1.40}z_{13.7}^{0.20}\nu_{10.3}^{0.20}$$
$$-\ 71\ {\rm mJy}\ (q_{0.5}L_{41.5})^{1.45}\mu_{p/e}^{0.81}x_e^{1.89}z_{13.7}^{0.19}\nu_{10.3}^{0.19}, \qquad (12)$$

for a distance $D = 3.25$ Mpc, and $i = (20°, 40°, 60°)$, respectively. This means that the resulting spectrum is no longer flat but tends to be inverted with $\alpha \sim 0.15$–0.27 for $i = 30°$–$90°$. The spectral index, like the size index, is a function of the

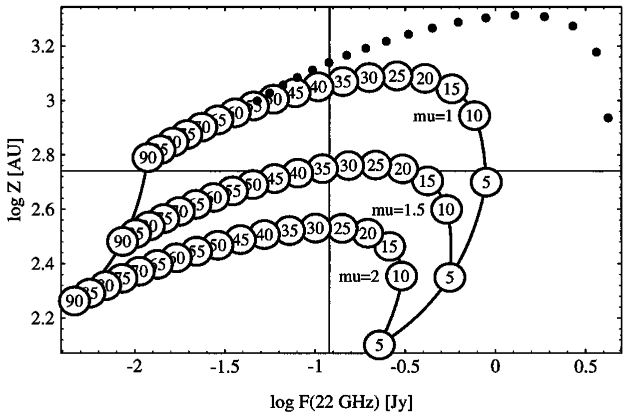

FIG. 1.—Parameter space for the jet-disk symbiosis model for M81* (D = 3.25 Mpc, $L_{\rm disk} = 10^{41.5}$ ergs s^{-1}); the vertical axis gives the size, and the horizontal axis gives the flux of the radio core. Values predicted by the model are calculated for various inclination angles (*circles*) and proton/electron ratios $\mu_{p/e}$. The corresponding predicted spectral and size indices depend almost exclusively on i and are α = (0.03, 0.09, 0.15, 0.19, 0.21, 0.23, 0.25, 0.26, 0.27) and m = (−0.98, −0.95, −0.92, −0.9, −0.89, −0.89, −0.88, −0.88, −0.88) for inclination angles i = 10°–90° in steps of 10°. A model without longitudinal pressure gradient would have predicted $\alpha = 0$ and $m = -1$ for all i. The black dots indicate how the parameter plane shifts if one increases the jet power ($q_{j/l} L_{\rm disk}$) by a factor 3.

inclination angle of the jet and tends to become flatter for smaller i.

3. APPLICATION TO M81*

We can now apply this formalism to the situation in M81*, where we have five observed quantities, namely, the time-averaged spectral index $\alpha \sim 0.2 \pm 0.2$ (Reuter & Lesch 1996), the flux F_ν(22 GHz) ≃ 120 mJy, the size z(22 GHz) ≃ 550 AU, the frequency dependence of the size $z \propto \nu^m$ with $m = -0.8 \pm 0.05$ (Bietenholz et al. 1996), and the bolometric luminosity of the nuclear source (Ho et al. 1996), which is $L_{\rm disk} \sim 10^{41.5}$ ergs s^{-1}.

Most of the model parameters are already well constrained. Since the cosmic-ray ratio $\mu_{p/e}$ and the fractional number of electrons x_e are almost interchangeable, we keep the latter fixed at $x_e = 1$. The jet-disk ratio $q_{j/l}$ was determined in FMB95 to be ∼0.15 for a flat spectrum. To bring this model with an inverted spectrum and a peak at submillimeter wavelengths to the same flux scale, one has to increase this value to $q_{j/l} = 0.5$, where the disk luminosity and the jet have equal powers; here we do not intend to change this value. The size of the nozzle z_0 enters only weakly into the equations; if we assume that the high-frequency cutoff, which is somewhere around 1000 GHz, corresponds to the size scale of the nozzle (analogous to Sgr A* in Falcke 1996a), we find by extrapolation that $z_0 \sim 3$ AU as an order of magnitude estimate. For a nozzle size of 10–100 gravitational radii, this corresponds to black hole masses of (0.3–3) × 10^7 $M_\odot$, which is consistent with dynamical estimates (Ho et al. 1996).

This leaves us with two main input parameters: i and $\mu_{p/e}$. The cosmic-ray ratio determines the electron Lorentz factor and is well constrained; by definition, $\mu_{p/e} \geq 1$, and from the condition $\nu_{\rm ssa} < \nu_c$, we here have $\mu_{p/e} \lesssim 3x_e^{-6/5}$ (eqs. [7] and [8]). Figure 1 shows the predicted sizes and fluxes of the model for various $\mu_{p/e}$ and i, indicating that in M81* $i \sim$ 30°–40° and $\mu_{p/e} \sim 1.5$ (FMB95 used $\mu_{p/e} = 2$ for quasars). The predicted spectral index then is $\alpha \sim$ 0.15–0.19, and the predicted size index is $-m$ = 0.9–0.92. Considering the simplicity of the model, those values are reasonably close to the observed ones.

4. DISCUSSION

The jet-disk symbiosis emission model by FMB93 and FB95, which was initially developed to explain the radio core of Sgr A* and radio-loud quasars, can also explain the nuclear radio source in M81 in detail. Simply by scaling the accretion disk luminosity by several powers of 10 to the observed value, one can correctly predict flux, size, spectral index, and size index of M81* as measured by VLBI.

If one inserts M81* into the universal $L_{\rm disk}$/radio correlation presented in Falcke & Biermann (1996), it falls right onto the line that connects Sgr A* and radio-loud quasars.[1] This suggests that all these sources are powered by a very similar engine. In this context, it is quite interesting to note that M81* and Sgr A* are in spiral galaxies yet appear radio loud in these diagrams. M81 also has recently shown double-peaked broad emission lines, a feature usually seen only in radio-loud galaxies (Bower et al. 1996).

Like in quasars and Sgr A*, one has to choose the most efficient, equipartition jet model to explain M81*, with high internal energy and a jet power that equals the disk luminosity. This leaves one with no free parameters for M81* other than the jet inclination angle, which, according to the current model, is around $i \sim$ 30°–40°. Some caution, however, is necessary, since the position angle of the VLBI component seems to change with frequency, something we have ignored here. It is not clear whether this indicates bending, helical motion, or an extrinsic effect and thus is difficult to interpret. Some of these effects could change the results slightly, but not to an order of magnitude.

In this Letter we have considered for the first time the effects of the longitudinal pressure gradient in the BK79 and FB95 jet model. Without any sophisticated mechanisms, this gradient alone will already lead to a moderate acceleration of the jet to bulk Lorentz factors of 2–3. Consequently, the Lorentz factor will increase toward lower frequencies, and for a fixed viewing angle outside the boosting cone, the flux will become Doppler-dimmed with respect to higher frequencies. This can provide a natural explanation for the inverted spectrum generally seen in compact radio cores and particularly for the size-frequency relation of M81*. Such a mildly accelerating jet may also be of interest for quasar and BL Lac radio cores or Galactic jet sources. The biggest advantage, however, is that the jet velocity, which was previously a free parameter, now is fixed by a simple physical model.

Another interesting point of the presented model is the usage of an initial, quasi-monoenergetic electron distribution for which we find $\gamma_e \sim 200$. This not only reduces another free parameter (the electron distribution index) but also can explain the submillimeter-IR cutoffs seen in Sgr A* and M81*. If the jet in M81* does not have strong shocks to reaccelerate those electrons into the usual power law, the jet would have size-dependent high-frequency cutoffs and thus explain the apparent absence of extended VLBI components in M81*.

This research was supported by NASA under grants NAGW-3268 and NAG 8-1027. I thank an anonymous referee for helpful comments, and P. Biermann, W. Duschl, H. Lesch, P. Mezger, and A. Wilson for numerous discussions.

[1] This was already shown in a preliminary way in Falcke (1994, Fig. 8.1).

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