Exploring jet properties in magnetohydrodynamics with gravity
Polko, P.

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Discussion and conclusions

In the work presented here we set out to develop a relativistic MHD jet model that includes gravity and, within this model, determine the location of particle acceleration. Here we first provide the general context of the research. Subsequently we give a summary of our main findings and discuss how this research can be used in the future and the possible implications.

There are several important outstanding problems in astrophysics to which our research is relevant. The hot gas surrounding galaxies should cool relatively quickly by emitting X-rays. This cool gas is then expected to fall towards the centre of the galaxy and form stars. However, this star formation is not observed and the gas remains hot despite the energy emitted. The most likely culprit is the jet produced by the central supermassive black hole. By supplying the surrounding matter with copious amounts of kinetic and electromagnetic energy, the jet can prevent the gas to cool down and collapse to form stars.

A second topic of intense study is the origin of ultra-high energy cosmic rays. There are preciously few sites that are energetic enough to provide these particles with the energies observed. Again the most likely source is jets in AGN, with Centaurus A receiving a great deal of attention as a possible source due to its proximity. These cosmic rays are believed to be accelerated by shocks in the jet. In both problems it is very important to know the energetics of the jet and the processes by which particles are accelerated. These are two aspects our research can contribute to.

Another question is the location where this particle acceleration takes place. VLBI observations (Junor et al. 1999; Walker et al. 2008) and spectral fitting (Markoff et al. 2001, 2005; Maitra et al. 2009a) suggest that this location is offset from the black hole at a distance of 10–1000 gravitational radii. We have shown it is possible to connect this location with the conditions close to the black hole.
There are several models for the accretion flow powering the jet. These accretion models provide the boundary conditions for the formation of a jet. Since, based on these boundary conditions, our work produces a unique jet flow solution up until the location of particle acceleration, with the constraints provided by the broadband spectrum, it may be possible to rule out certain accretion flow models.

In the mathematical description of a magnetohydrodynamic flow, such as a jet, three singular points appear. This singular points have important physical implications. The modified slow point, occurring very close to the black hole, provides a convenient location to connect our jet flow solution with an accretion model. This connection provides the necessary information to completely specify the resulting jet. The modified fast point is the location where the flow becomes causally disconnected. Anything happening beyond this location cannot affect the flow closer to the black hole. It is therefore necessary to cross this point before a stable shock, able to accelerate particles, can exist.

We have shown for the first time that it is possible to cross the modified fast point using a relativistic magnetohydrodynamical formalism. Every solution found eventually overcollimates and returns to the axis of symmetry. While this result may be due to the requirement that the modified fast point lies at a finite height, it does allow the possibility of a stable collimation shock capable of accelerating particles. Such a collimation shock is thus an integral element of our formalism. Without gravity, however, it is impossible to have a reliable jet solution close to the black hole and therefore to connect the location of this stable shock to the conditions at the base of the jet. By including gravity into our formalism, we were able to finally make this connection.

By the inclusion of gravity we have broken one of the assumptions of the formalism, the assumption of self-similarity, which means that by a simple scaling any field line can be scaled to every other field line in the jet. By breaking this assumption, a single solution does no longer suffice to specify the entire jet. Instead we need to calculate several solutions, all at different radii, to be able to describe a jet. We have found that choosing two specific model parameters to fit for the modified slow and fast point, namely the ratio of the radius of the Alfvén point and that of the light cylinder radius, and the adiabat describing the temperature of the jet, it is possible to very closely approximate self-similarity. However, the value of the adiabat can vary significantly across the field lines, meaning the matter transported along the outer field lines is colder than it should be compared to the matter on the inner field lines.

While our aim is to find solutions where a shock may form at 10–1000 gravitational radii, so far we have no found solutions much below 900 gravitational radii. Looking at the effects the model parameters have on this height, it seems the best approach to finding solutions with smaller heights, is by moving the Alfvén point
closer to the disc and having a more cylindrical jet. We have not found solutions with Lorentz factors higher than 1.6, too low for some X-ray binaries and most active galactic nuclei. These low Lorentz factors are due to a low value magnetisation parameter. Since there is little magnetic energy in the jet, the matter cannot be magnetically accelerated to high velocities. Finding solutions with a higher magnetisation parameter is therefore the best strategy to obtain higher Lorentz factors.

This change in distribution has a significant effect on the synchrotron contribution to the overall spectrum. A quasi-thermal distribution has a corresponding exponentially decreasing flux at the high-energy end, strongly localising the frequency of the emission based on the magnetic field strength. In contrast, the accelerated distribution also causes a power-law component above the frequency for which the jet becomes optically thin, with a spectral slope $S_{\nu} \propto \nu^{-(p-1)/2}$, where $p$ is the power-law index of the energy distribution ($dn = N_0 E^{-p} dE$). This power-law component can extend to appreciably high frequencies, with the highest contribution from the location where the particles first get accelerated, due to the higher field strength there. Thus the height of this location determines the contribution to the, in the case of XRBs, X-ray emission from synchrotron emission produced in the jet. For the same observed X-ray flux, a higher height would increase the need for an alternative source of emission, such as inverse Compton. Constraining the height of this location by self-consistently deriving the height of the MFP can therefore give us essential information about which emission mechanisms are important and the prevailing conditions in the jet and disc.

The analytical power of this model truly comes into its own when used as part of a spectral fitting code. This code, although expanded and refined over the years (Falcke & Biermann 1995; Falcke 1996; Falcke & Markoff 2000; Markoff et al. 2001, 2003, 2005, 2008; Maitra et al. 2009a), was originally developed to test the hypothesis that the hot magnetised corona could be the base of the jet, called the jet-disc symbiosis. It determines the spectral contributions from an accretion disc and the jet and takes different radiative processes into account. By comparing the calculated spectrum to those of observed black hole systems, it is possible to constrain several properties of the system. For example, the height of the start of the particle acceleration region regulates the contribution of the jet to the X-ray bands. Since we are able to determine this height self-consistently, we will be able to determine the relative importance of the radiative processes contributing to the X-ray.

However, the jet in this code is described by a hydrodynamical model (Falcke & Biermann 1995; Falcke & Markoff 2000), so the magnetic field does not accelerate or collimate the jet. Moving to a magnetohydrodynamical model has several clear advantages. First, the magnetic fields are treated in a self-consistent way, providing acceleration and determining the geometry of the jet. Second, the height of the
acceleration region becomes a derived quantity and is removed as a free parameter. The additional four free parameters from the MHD model can be tied to the magnetic field strength, the temperature, the density and the initial velocity at the base of the jet, and thus do not contribute to the total number of free parameters. Third, we will be able to calculate the power of the jet independently, giving us a better handle on AGN feedback and cosmic ray energies. Fourth, there are fewer limitations to the environments that can be modelled, as either the velocity, the magnetic field, the gravitational potential, or all can attain relativistic energies. We can therefore apply the code to an even greater variety of sources of both mass scales. In this way we can test the similarities and theoretical scalings among them, extending the fundamental plane of black hole accretion. This should give us new insights into the physics of jet launching.
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6 Discussion and conclusions