PHYSICS OF THE M87 JET

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Motivated by the recent determination of proper motions of knots in the M87 jet by Biretta, Zhou, & Owen (1995), we have investigated the relationship between the dynamics of the jet and the kpc-scale radio and optical structure. We interpret the knots as internal shocks in the jet, and find that relativistic effects play an important role in their appearance. In particular, knot A, which appears to be almost transverse to the flow and seems to be viewed nearly edge-on, is in fact a highly oblique shock. The direction of its normal with respect to the flow lies within about 10° of the Mach angle, i.e., the angle of obliquity beyond which no shock is possible. In a frame comoving with the shock front, the incident streamlines make an angle of about 40° – 60° with respect to the shock normal. Knot A has a proper motion corresponding to only $0.51c$, and the relativistic effects are modest. Its edge-on appearance is largely fortuitous. We have found, however, that relativistic effects would create a strong bias for shocks with apparent *superluminal* speeds to appear nearly edge-on.

A modest pressure jump of roughly a factor of 5 at knot A is adequate to explain the enhanced synchrotron emissivity, by amplifying the magnetic field and boosting the energies of the upstream population of relativistic electrons. Synchrotron emissivity will be strongly enhanced even if diffusive shock acceleration is inefficient, since the relativistic electrons still undergo shock–drift acceleration (Begelman & Kirk 1990). The required level of compression is consistent with the observed proper motion and small jet deflection, if the jet Lorentz factor is of the order of 3 – 5. Other knots in the M87 jet, as well as the faint striations observed all along the jet (which

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give the impression of helical filaments wound around the jet), could also be oblique shocks.

The observed spectral break frequencies of knots A and B (Biretta, Stern, & Harris 1991) are consistent with particle acceleration at the shock front followed by synchrotron cooling in the post-shock magnetic field, if we assume both that the Lorentz factor exceeds 2 in the post-shock flow and also that the magnetic field is comparable to the equipartition value corrected for relativistic beaming.

We suggest that the nonlinear development of the Kelvin-Helmholtz instability is responsible for triggering the oblique shocks. From the knot proper motions and jet morphology (Owen, Hardee, & Cornwell 1989), we estimate the real and imaginary wavenumbers and group velocity of the most unstable mode. Working backward through the dispersion relation for the instability, we can constrain both the ratio of "cold" to relativistic material inside the jet and the ratio of jet to ambient density. According to this analysis, the M87 jet is composed of a rather relativistic fluid, with an internal sound speed greater than $c/3$ (as compared with an ultrarelativistic fluid, which has sound speed $c/\sqrt{3}$). It propagates through a medium whose density is no more than 10–100 times that of the jet. This implies that the kpc-scale radio lobes are much less dense than the interstellar medium (ISM) in the central regions of the M87 cooling flow. The radio jets in M87 are therefore driving high pressure, low-density bubbles into the surrounding ISM. The radii of the lobes are consistent with this assertion and the inferred energy flux in the jet if the age of the source is $\sim 10^6$ yr, consistent with that estimated by Turland (1975). The resultant expansion of the lobes can comfortably power the excitation of the surrounding optical filaments by driving radiative shocks into preexisting condensations.

Readers desiring more detailed information about this work should consult our recent manuscript (Bicknell & Begelman 1995).

References

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