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Weak headed quasars

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Abstract. We use the published VLA maps of high luminosity, steep-spectrum radio quasars showing prominent kiloparsec-scale one-sided jets, but faint hot-spots (i.e., weak-headed quasars) to call into question the common perception that the mechanism leading to such unusual morphologies is the strong dissipation of the jet's power through a vigorous entrainment of thermal gas by the initially relativistic jet. Under this hypothesis nearly half of the weak-headed quasars would be predicted to exhibit two-sided jets, one of which is actually receding from us, but is made visible nonetheless due to the postulated strong dissipation. However, no example of a source with two-sided jets is found in a well mapped representative sample of 8 weak-headed quasars. Evidently, the prominent appearance of their (all one-sided) jets is still largely due to relativistic bulk flow. We therefore suggest that the anomalous weakness of the heads of the jets is probably linked to the weakening of the Mach disk, following the onset of decollimation of the jet's working surface as its forward motion slows down to nearly subsonic speed. We outline some potentially interesting observable consequences of this scenario. Weak-headed quasars, which seem to be a substantial subset of the steep-spectrum quasar population at large redshifts, could provide important clues on the late evolutionary stages of powerful radio sources.

Key words: galaxies: active – galaxies: jets – quasars: general – radio continuum: galaxies

1. Introduction

A remarkable feature of powerful extragalactic double radio sources (FR II type) is the presence of bright spots of emission near the outer edges of their radio lobes. These hot-spots, with a typical extent of $\sim$1 kpc are believed to be the working surface where the (supersonic) jet decelerates and its plasma is thermalized at the Mach disk (e.g. Begelman et al. 1984). Other high surface brightness features often seen in the radio images of quasars (QSRs) are the compact core and a (relativistic) jet extended towards one of the radio lobes; the other jet is believed to be moving away from us, and hence, severely Doppler dimmed. In steep-spectrum QSRs the hot-spots are usually distinctly brighter than the jet at gigahertz frequencies (e.g., Bridle et al. 1994). So it is remarkable that in a sample of high redshift ($z > 1.5$), steep-spectrum QSRs a significant fraction ($\sim$10%) has been found to lack clearly identifiable hot-spots on the jetted side (Lonsdale et al. 1993: LBM). Controversial inferences about the nature of such QSRs have emerged from the reported studies, each based on just one or two cases. For instance, the abnormal prominence of the jet vis-à-vis the hot-spot in 3C 280.1 is attributed by Swarup et al. (1982) to a strong dissipational loss of the the jet's kinetic energy during transit to the hot-spot. Similar arguments for the QSR 1857+566 were made by Saikia et al. (1983). While this may be true in individual cases, Akujor & Garrington (1991), based on their analyses of hydrodynamic instabilities, disfavour this possibility and, instead, argue that relativistic beaming of the jet is the factor chiefly responsible for enhancing the contrast between the jet and the hot-spot. To investigate this important question, we present here phenomenological arguments employing a representative sample of 8 high luminosity weak-headed quasars, which suggest that in general their prominent extended jets are relativistic and the inability to form a bright terminal hot-spot stems from the slowing down of the advance of the jet's front to below the trans-sonic limit, resulting in a rapid decay of the head (i.e., the "hot-spot").

In the currently favoured unified scheme for powerful extragalactic radio sources (see recent reviews by Urry & Padovani 1995; Gopal-Krishna 1995; 1996), the nearly universal one-sidedness of jets in QSRs is explained by positing that all QSRs are viewed within about 45° of the nuclear symmetry axis (Barthel 1989; Antonucci & Barvainis 1990; Padovani & Urry 1992), though this angle appears to correlate positively with the beam power (e.g., Gopal-Krishna et al. 1996 and references therein).

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Thus, through Doppler favoritism (e.g., Scheuer & Readhead 1979; Blandford & Königl 1979), the approaching jet appears much brighter than the receding jet even though their hot-spots typically appear quite similar. There is now substantial evidence in favour of bulk relativistic speeds in powerful jets persisting to kiloparsec-scales (Bridle et al. 1994; Laing 1994; Urry & Padovani 1995; Scheuer 1987). The jets seem to start out relativistic (i.e., apparently one-sided) even for the weaker FR I sources which, however, have emission dominated by two-sided jets on larger scales (e.g., Laing 1994; Parma et al. 1996; Giovannini et al. 1996), and therefore it has been argued that the two types of jets are basically identical (Bicknell 1994; Laing 1994; Giovannini et al. 1996; Gopal-Krishna & Wiita 1988), although this contention is by no means universally accepted (e.g. Baum et al. 1995).

The usual explanation for the jet power related difference between FR I's and FR II's is that the weaker jets are unable to terminate in bright hot-spots, since they are more prone to entrain external gas through surface instabilities, thereby dissipating their kinetic power rapidly and slowing down to non-relativistic speeds (e.g. Bicknell 1994; Laing 1994; De Young 1993; also, Komissarov 1994). An inevitable outcome of any dissipation process would be to render the jet radiation increasingly isotropic before the fading of its head, due to the loss of jet power in transit, ensues. Since the dissipation is equally likely to operate on either side of the nucleus, the above hypothesis for the slowing down of jets implies that we should also see QSRs in which the receding jet is rendered visible due to dissipation and deceleration, in addition to the approaching jet, which is visible on account of relativistic beaming, even if its dissipation is yet to set in. It is therefore important to search for examples of QSRs showing two-sided jets with relatively weak hot-spot(s), which would be a signature of the postulated jet dissipation scenario.

2. Characteristics of weak-headed quasars: WHQs

To look for such QSR candidates one would prefer a low-frequency selected sample (so that hot-spots are not discriminated against) mapped with high angular resolution. LBM have published VLA maps (A array, 5 GHz) of 79 out of all the reported 81 steep-spectrum ($\alpha < -0.6$, with $S_\nu \propto \nu^\alpha$) quasars having $z > 1.5$. Of these, 74 QSRs were also mapped by them at 15 GHz. These 79 QSRs are powerful radio sources, with all but one falling in the relatively narrow luminosity range $10^{26.6}$ W Hz^{-1} $< P <$ $10^{28.6}$W Hz^{-1} at 15 GHz in the emitted frame (taking $H_0 = 75$ km s^{-1}Mpc^{-1} and $q_0 = 0.05$), and thus well above the FR I/FR II transition luminosity, where hot-spots are typically the dominant feature outside the core. LBM noted that a non-trivial fraction (8 "clear" cases and a few potential ones), which we term as weak-headed quasars (WHQs), show the unusual property that their (one-sided) jets are very prominent but do not terminate in a conspicuous hot-spot. If indeed such a morphology arises from excessive energy dissipation of the jets in transit, then some of these jets can be expected to be on the far side of the nucleus and yet be visible, thanks to the dissipation. However, in no case is the putative approaching counterpart of any such jet (whose radiation would be relativistically beamed in our direction) detected, as well. This negative result, namely the non-detection of two-sided jets in any of the WHQs, strongly suggests that even in WHQs the observed (bright) jets are in general the approaching ones (i.e., relativistically boosted), with the implication that the dissipative jet scenario (e.g. Swarup et al. 1982; Saikia et al. 1983; LBM) may not be, in general, a viable explanation for the marked weakness of the heads, albeit it may work in some individual cases (see below).

From the radio contour maps of the 8 WHQs (cf. LBM), we estimate that the jet's peak surface brightness at 5 GHz always exceeds the maximum of its head by a factor between 2 and 30 at 5 GHz. But, in all cases the (invisible) counter-jet is found to produce a fairly well detected hot-spot and lobe. Further, for all the WHQs, the brightest portions of the jets are comparable (to within a factor between 0.25 and 4) in brightness to the core; this is also anomalous, for in the remaining QSRs of the LBM sample the core is found to be distinctly brighter than any part of the jet. Finally, we note that at 5 and 15 GHz the polarization vectors in the jets of all of these WHQs reveal that the magnetic field is aligned with the jet's trajectory, as is characteristic of FR II sources, that is to say, of presumably relativistic, jets.

3. Difficulties with the jet dissipation hypothesis and a potential alternative scenario

As argued above, the observed side-to-side asymmetry of jets in this representative sample of 8 WHQs appears to run counter to the conventional wisdom according to which a jet's extraordinary prominence arises from entrainment induced enhanced dissipation of the jet power, which slows it down to non-relativistic speeds and leads to a weaker hot-spot formation, analogous to the situation proposed for low luminosity FR I sources. Other conceivable explanations for the anomalous faintness of the hot-spot on the jetted side include: (1) Much of the hot-spot emission is beamed away from us, which is possible if the backflow is very strong (cf. Tribble 1992, who discussed the possibility that hot-spots could even exhibit central emission dips); however, this seems unlikely to be effective enough to hide an approaching hot-spot (see below). (2) The hot-spot has a much steeper spectral index than its jet, so that it appears much fainter at the relatively high frequency at which it is being observed in the rest-frame of the QSR; however, in this case it would be surprising that the hot-spot on the other side is usually quite distinct. This possibility can be further examined by making maps at lower frequencies, though it may be recalled that the extraordinary prominence of the jets is not merely relative to the hot-spots, but also relative to the core, which is expected to have a flatter spectrum. (3) The ambient gas density distribution around the AGN could itself be asymmetric, causing a stronger jet dissipation on the denser side. While fortuitously possible, this again would require that in all 8 WHQs such dissipation is effectively occurring only on the side towards us, for otherwise, in 50% of the cases we should see not only the receding dissipative jet, but also its approaching, relativistically beamed, counterpart. (4) Effects similar to 3) could be caused if the observed jet were intrinsically the weaker one (so that it entrained more effectively) and/or less well collimated, so that its thrust was spread over a larger area than that of the other jet. However, the problems with possibility 3) recur for these other ways of inducing intrinsic asymmetries.

Note that the evidence for jet deceleration to non-relativistic speeds on kiloparsec scales in the case of edge-darkened FR I sources (Sect. 1) raises the question whether the same could also be happening in WHQs, in which case the argument against possibility (3) mentioned above would not be relevant. The tacit assumption therein of relativistically beamed large scale jets could actually be verified by demonstrating the sidedness correlation of parsec and kiloparsec scale jets in individual WHQs, as found for virtually all normal quasars (Scheuer 1987). Unfortunately, the required VLBI images are not yet available. Nonetheless, support for our contention that the extended jets in the WHQs are relativistic comes from the radio polarization imaging observations which are available for 4 out of the total 8 WHQs (see below). These four WHQs are: 0017+154 (3C9), 1258+404 (3C280.1), 1318+113 (4C11.45) and 1323+655 (4C65.15). As seen from Table 6 of Garrington et al. (1991), the polarization maps at $\lambda = 6$ and 20 cm imply that in each of these 4 WHQs the estimated Faraday dispersion parameter for the extended radio emission on the counter-jet side is a factor of 1.8 to >3.6 greater than for the jet side (i.e., the Laing-Garrington effect; Laing 1988; Garrington et al. 1988). This is precisely what would be expected if in each case the observed kiloparsec scale jet were located on our side of the nucleus; then its visibility can be most simply explained in terms of relativistic bulk motion of the jet plasma, as assumed in the present discussion.

The above arguments suggest that the remarkable prominence of jets in the WHQs may not be the result of the jet flow being slowed down to non-relativistic velocities (via excessive entrainment/dissipation). We suggest that given the observational constraints mentioned above, the abnormal faintness of the hot-spot on the jetted side could be more readily understood if the advance speed of the hot-spot in these sources has dropped to a value comparable to the sound speed of the ambient medium (e.g., Gopal-Krishna & Wiita 1988; Leahy 1990; Gopal-Krishna 1991; Roland et al. 1992; Blandford 1996). This would lead to the disappearance of the bow-shock and consequently a fading of the lobe through rapid expansion, perhaps exacerbated by enhanced radiative losses through inverse Compton scattering on the microwave background photons, particularly at the high redshifts of these QSRs (Gopal-Krishna & Wiita 1988; Gopal-Krishna et al. 1989). Conceivably, such an evolutionary pattern would induce a disruptive feedback on the jet's stability and collimation, which would be greatly weakened while the terminal Mach disk decays due to transverse expansion of the jet's front, leading to diminution of the associated hot-spot.

A related point to note here is that while bending of a jet with substantial Doppler factor might be expected to cause very large variations in the observed surface brightness along the bends, which are often not observed (e.g., van Groningen et al. 1982; Scheuer 1987), in reality, a range of Lorentz factors will be present within the jet flow, so that its forward-beaming pattern will be considerably broadened (e.g., Lind & Blandford 1985; Vermeulen & Cohen 1994; Laing 1995). A similar, or larger broadening can therefore be expected also for the hot-spot emission pattern, making it difficult to hide the approaching hot-spot (cf. alternative (1) above).

Since, under the beaming hypothesis, the jetted side is always the one nearer to us, it is seen at a later stage in the source evolution (compared to the other side). This time-lag would facilitate the viewing of the shock front's disruption and weakening of the hot-spot on the jet's side. Conversely, the receding jet will be viewed at an earlier evolutionary stage, so that, provided the hot-spots on the two sides have identical evolutionary histories, the receding one, being monitored at an earlier phase of decay may appear more conspicuous than its approaching counterpart. We also point out that the expansion of the lobe will reduce the transverse impact that motions in the cocoon have upon the jet (e.g. Hooda & Wiita 1996), thereby weakening many of the internal shocks that cause the jet to emit from knots associated with internal bi-conical structures (e.g. Norman et al. 1982), so that the emission from the jet itself will also begin to fade soon afterwards. Therefore, we identify WHQs as *transition cases* in which the jet flow is still relativistic but the front of the jet is in the process of getting decollimated, with the consequence that the head is no longer radiating so powerfully.

This hypothesis is supported by the observed arm-length ratios for the WHQs, which, although hard to define in the absence of a bright spot at the jet's end, can be conservatively estimated by measuring distance from the detected radio core to the brightest significant peak found near the jet's extremity. Of the 8 WHQs enumerated by LBM, 5 have the arm-length clearly more on the jetted side (0017+154, $D_j/D_{hs} = 1.53$; 0038−019, 1.24; 0730+257, 1.62; 1323+655, 1.57; 1857+566, 1.10), two have a ratio marginally less than unity (1258+404, 0.93; 1318+113, 0.93) and the ratio is well below unity in just one case (1345+584; 0.29). However, as seen from Figs.

104 and 105 of LBM, the jet in 1345+584 shows a strong U-shaped bend so that its arm-length ratio may well have been drastically underestimated, and we do not regard this source as a clear counter-example to the trend of the jetted sides appearing longer. Thus, these data are also broadly consistent with the idea that the hot-spot associated with the putative counter-jet is being viewed at an earlier stage in the source evolution than the head of the observed jet. We note that in four cases (1318+113 and 1345+584 again, as well as 1323+655 and 1857+566) sharp bends are observed roughly midway along the jets, conceivably due to a collision with another galaxy, or massive gas cloud, as argued for the QSR 1857+566 by Saikia et al. (1983) and for the radio galaxy 1222+216 by Saikia et al. (1993). Thus we do not totally discount the possibility that an asymmetric environment plays some role in these cases. Nonetheless, any such putative collisions are clearly not severe enough to immediately disrupt the powerful jet or render its receding counterpart visible.

4. Summary and general remarks

The morphological characteristics of weak-headed quasars highlighted in this study cast some doubt on the validity of the widely held notion that a strong dissipation of the relativistic jet's power, induced by entrainment of thermal gas into the jet flow, is the causal event responsible for the lack of a prominent hot-spot at the end of the jet, as witnessed in several highly luminous radio quasars. We have argued that the outflow in these wiggling jets with abnormally weak hot-spots is probably still dominated by relativistic beaming effects, and the anomalous weakness of their heads could either be because the radiation of the heads is beamed away from us, or, more likely, because the jet's advance has become subsonic, with the consequence that its front is beginning to get decollimated. Visualizing the final evolutionary phase of such sources, the poorly confined, fading cocoon engendered by the decollimating jet-front will not be able to help maintain the jet's stability farther back, where the impact of cocoon vortices normally give rise to internal bi-conical shocks (e.g. Norman et al. 1982; Hooda & Wiita 1996), so that the jet emission itself will begin to weaken subsequently. At even later (observed) times, the same fading will be seen to afflict the receding jet as well; but by then the approaching jet may well have expanded and faded beyond detection at gigahertz frequencies. Thus, it is tempting to speculate that, during this limiting phase, some QSRs might still exhibit a one-sided jet, albeit the receding one, which is by then rendered visible due to excessive dissipation.

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