Orientation and size of the ‘Z’ in X-shaped radio galaxies

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1 INTRODUCTION

A small subclass of radio galaxies is formed by the X-shaped radio galaxies (XRGs), which all have radio luminosities close to the FR I/II transition of $10^{25}$ W/Hz at 178 MHz (Fanaroff & Riley 1974). These sources show two misaligned pairs of radio lobes of comparable extent (e.g., Ekers et al. 1978; Leahy & Parma 1992), which have also been referred to as wings and appear as X-shaped structures. After the discovery of this class of sources various mechanisms for their formation have been proposed. Here we give only a short summary, for a more detailed discussion see e.g., Rottmann (2001) or Dennett-Thorpe et al. (2002).

According to the backflow model by Leahy & Williams (1984) jet material is streaming from the hot spots of the primary lobes back towards the host galaxy. It remains collimated until it hits the backflow from the opposite lobe and then expands laterally in a fat disk perpendicular to the radio lobes. It is not clear in this model how the plasma, falling back on the disk, can be diverted to just one side of the primary lobes in order to form the X-shape. Moreover this mechanism can not explain that the secondary lobes extend as far or even farther than the primary lobes and how such an extension can be achieved with subsonic velocities within the life-time of the radio source.

The buoyancy model suggests that the radio lobes have a lower density than the ambient medium, resulting in buoyant forces (Gull & Northover 1973; Cowie & McKee 1975), which are thought to bend the lobes towards regions that provide density equilibrium. This model has the same problems as the backflow model to explain the symmetry of XRGs and the extension of the secondary lobes.

Apparentely the radio jets, which are assumed to be aligned with the spin of the black hole at their origin (Wilson & Colbert 1995), have been stable for a long time span before undergoing a short period of reorientation into another stable state (Rottmann 2001). This can not be explained by a steady precession as has been originally done by Ekers et al. (1978). Gower et al. (1982) applied a precessing jet model to various galaxies, among them NGC 326. Though the wings could be reproduced the inner symmetry is rotated by about 45°. Also according to present day deep radio images of NGC 326 a precessing jet seems to be highly unlikely the cause for its shape (Rottmann 2001). An interesting idea, pointed out by the referee, is whether such a
structure could be related to the combination of a precessing jet and the recoil suffered by the merged black hole due to anisotropic emission of gravitational waves (e.g. Blandford 1979). Without going into the details, what would be beyond the scope of this article, it does not seem to be very likely for both the sources we are interested in here. Such a kick would give the black hole, i.e. the source of the post-merger jet, a linear momentum and hence break the symmetry. Though this might explain the apparent curve close to the center in the post-merger jet of NGC 326, generally both jet pairs are seen to be symmetrical about the common center. The symmetry can rather be explained by rapid realignment of the jet due to accretion from a misaligned disk or the coalescence of a supermassive binary black hole (BBH) on time scales less than $10^7$ yr (Rottmann 2001; Zier & Biermann 2001, 2002). Such a BBH is formed previously in a merger of two galaxies each of which host one of the supermassive black holes (SMBH) in their center (Begelman et al. 1980). The final stage of the merger is dominated by emission of gravitational radiation which leaves the spin of the resulting SMBH aligned with the orbital angular momentum $\mathbf{L}_{\text{orb}}$ of the binary (Rottmann 2001; Zier & Biermann 2001, 2002; Chirvaseso 2002; Biermann et al. 2002). After a short time a new jet will propagate along the spin axis, i.e. the jet flips from the direction of the spin of the pre-merger SMBH in the direction of $\mathbf{L}_{\text{orb}}$ (see Fig. 9 in Zier & Biermann 2002). These ideas were also explored by Merritt & Ekers (2002).

In at least two XRGs the ridges of the secondary lobes have been observed to be offset from each other laterally by about their width, hence showing a Z-shaped symmetry about the nucleus (Fig. 1). Because a high angular resolution as well as a rather special aspect angle are necessary to see such an offset it is possible that a Z-symmetry is more common than current detections suggest. To explain this symmetry Gopal-Krishna et al. (2002) (hereafter G-KBW) propose some modifications to the spin-flip model outlined above: As the captured galaxy spirals to the common center it induces a rotational stream-field in the ambient medium on large scales. If the trajectory of the secondary galaxy passes through the polar regions of the primary, the motion of the ISM bends the original jet into Z-shape before the merger is completed. This means that purely Z-symmetric radio sources (i.e. without X-morphology) might be spotted before evolving to an XRG once the SMBHs have coalesced.

In the present article we will deproject the Z-shaped sources in order to understand their geometry and possible orientation to us. Of interest is the distance in which the old jet is bent into Z-shape since it gives us information about the strength of the jet and the properties of the gas stream in the wake of the secondary galaxy. Ultimately this contributes to our knowledge of the history of a merger between two galaxies.

In the next section we will explain the geometry of the jets and lobes and deduce limits for the involved angles before deriving the expressions for deprojecting the jets. In Sect. 3 we apply our model to the two Z-shaped sources NGC 326 and 3C 52. The results are discussed and compared with other observations in Sect. 4. A summary and conclusions are presented in Sect. 5.

2 JET ORIENTATIONS AND Z-SHAPES

2.1 The geometry of ZRGs

In order to observe a source as XRG both, the primary and secondary lobes, i.e. the post- and pre-merger lobes respectively, have to be close to the plane of sky. Both pairs also have to subtend a sufficiently large angle on the sky so that we can distinguish them. Because the pre-merger spin of the primary SMBH and the orbital angular momentum of the merging binary, defining the later post-merger SMBH spin, are not correlated, we expect the angle between them to be large on average. In his thesis Rottmann (2001) used statistical methods to estimate the most likely distribution of the intrinsic angle $\theta$ between both pairs of lobes. For this purpose he constructed a theoretical distribution of projected angles $\theta'$ for an ensemble of XRGs with intrinsic angles uniformly distributed between $\theta_1$ and $\theta_2$. Taking into account

Figure 1. Radio images of the two Z-shaped XRGs are shown. NGC 326 (Murgia et al. 2001) in the left panel at 1.4 GHz and 3C 52 (Leahy & Williams 1984) in the right at 1.6 GHz. In both sources the secondary lobes are weaker and their ridges have a lateral offset of about their width, forming a Z-shape. While in 3C 52 primary and secondary lobes have about the same extension, the secondary ones in NGC 326 are much more extended.
various selection effects (the projected angle should not be too small or large; inclination of the jets with respect to the plane of sky should be small; the projected length of the secondary lobe should not be too short) and comparing the theoretical results with the observed distribution he obtains the best fit if $60^\circ \lesssim \theta \lesssim 90^\circ$. This is in agreement with our expectation of the intrinsic angle to be large. However, Rottmann points out that the obtained distribution cannot reproduce the peak observed at $\sim 50^\circ$ in the distribution of the projected angle. He suggests that a non-uniform distribution of intrinsic angles will improve the fit.

Provided that the direction of the spin of the post-merger SMBH and hence also the direction of the post-merger jet are dominated by the orbital angular momentum of the binary, the directions of the pre- and post-merger jets are uncorrelated. This allows us to imagine both jets as a pair of uncorrelated arrows which we can superpose so that both their centers lie on each other and they enclose an angle in the range $0^\circ \lesssim \theta \lesssim 180^\circ$. Without loss of generality we fix one arrow to be aligned with the $z$-axis. Asking now for the distribution of the intrinsic angles between both arrows is like looking for the distribution of the pinholes the second arrow pierces through the surface of the unit-sphere. Since both arrows are uncorrelated this is analogue to a uniform distribution of stars projected on the unit-sphere. Therefore the probability to find a star or pinhole in a solid angle element $d\Omega = \sin \theta \, d\theta \, d\phi$ around the coordinates $(\theta, \phi)$ is

$$p(\theta, \phi) = \begin{cases} \frac{a^2}{4\pi} & 0 \leq \theta \leq \pi \quad \text{and} \quad 0 \leq \phi \leq 2\pi, \\ 0 & \text{otherwise.} \end{cases}$$

With the substitution $u = -\cos \theta$ a uniform distribution over the unit-sphere requires a uniform distribution of both coordinates in the ranges $-1 \leq u \leq 1$ and $0 \leq \phi \leq 2\pi$. Hence the intrinsic angle $\theta$, instead of being uniformly distributed, is distributed according to $p(\theta) = 1/2 \sin \theta$, peaking at $90^\circ$. The less the orbital angular momentum of the binary dominates the post-merger spin the more the maximum in the distribution of $\theta$ will shift to smaller angles and the more the distribution will deviate from a symmetric distribution about the maximum. Qualitatively this seems to be in good agreement with the observed distribution that Rottmann shows in his thesis. A careful comparison of the theoretical with the observed distribution could give a clue about the nature of the formation of XRGs and which component dominates the post-merger spin after the SMBHs have merged due to emission of gravitational radiation. But this requires much more and better data. We just keep the result in mind that the formation mechanism of XRGs is likely to create jet-pairs with large intrinsic angles, while both lobes have to be close to the plane of sky so that we can actually observe the X-shape.

As the secondary galaxy is spiraling into the common center of mass, it will generate a streaming motion in the merger plane due to mass loss and dragging along ISM of the primary galaxy. On large distances the density and velocity of the streaming motion will probably be strong enough to bend the jets into wings. As the the secondary galaxy spirals inwards to smaller distances the power of the jet will become stronger and beyond a certain distance no bending of the jet will be possible. In the following we will refer to the distance where the bending happens as $r$. The rotation stream will have some thickness $2h$ perpendicular to the merger plane and in the distance $r$ be roughly confined to the surface of a cylinder, which is aligned with the orbital angular momentum of the galaxies. The possible orientations of both jet-pairs and the line of sight (LOS) are shown in Fig. 2.

The $z$-axis is aligned with the orbital angular momentum and hence identified with the post-merger jet. With the bold solid circle we denote the merger plane and with the pair of uncorrelated arrows which we can superpose so that both their centers lie on each other and they enclose an angle in the range $0^\circ \leq \delta \leq 180^\circ$. The secondary lobes are bent in the distance $r$ by the clockwise rotating gas into the wings (following the solid circle (a, c) or the dashed one (b)). $h$ is the required minimum half-height of the rotating stream.

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**Figure 2.** Possible orientations (a, b, c) between primary lobes (aligned with the $z$-axis), the LOS ($\perp$ to the paper plane through the center) and the secondary lobes (in color or grey-shades) are shown. $\theta$ denotes angles to the $z$-axis, $\delta$ to the merger plane, so that $\theta + \delta = 90^\circ$. The secondary lobes are bent in the distance $r$ by the clockwise rotating gas into the wings (following the solid circle (a, c) or the dashed one (b)). $h$ is the required minimum half-height of the rotating stream.
our prediction for the intrinsic angle above and with the explanation of the Z-shape within the framework of the merger model. Hitting the rotation stream the pre-merger jet will be deflected into the wings at some angle which is determined by the relative strengths of the ram pressure of the rotating matter and the jet. For a weak jet the wings will be dragged along with the rotation stream and hence their projected extension would be limited by the radius of the stream. For NGC 326 and 3C 52 extensions of at least 50 and 100 kpc have been observed respectively. So we can conclude that either the bending happens on such large radii, or a stronger jet is deflected at a smaller angle. Fig. 1 shows that both wings lie close to the plane of sky and so we conclude that large radii of the rotating stream are more likely than small deflecting angles. Because \( \varphi \) is assumed to be 0, also the pre-merger jet lies in this plane and the wings are perpendicular to the paper plane. As in Fig. 2 the angles \( \delta \) and \( \theta \) in Fig. 3 denote the angle to the merger plane and z-axis respectively. See Fig. 3 for the meaning of the other quantities. Projecting the sum of the approaching and receding jet \( y_a \) and \( y_r \) in the plane of sky yields the wanted relation between \( \Theta_{\text{jet}} = \tan^{-1} \left( \frac{y_p}{r_D} \right) \), the bending radius \( r \) and the angles \( \theta_{\text{jet}} \) and \( \theta_{\text{LOS}} \).

**Orientation a:** (dotted blue/dark-grey lobes in Fig. 2)

With \( a = D \tan \delta_{\text{LOS}} \) and the definition \( k \equiv \tan \delta_{\text{jet}} = h/r \) we get from Fig. 3:

\[
\tan \delta_a = \frac{a - h}{D - r} = \frac{h - y_a}{r},
\]

which can be solved for \( y_a \):

\[
y_a = r \left( k - \frac{\tan \delta_{\text{LOS}} - k r/D}{1 - r/D} \right). \tag{1}
\]

In the same way we get for the receding part of the jet

\[
y_r = r \left( k - \frac{\tan \delta_{\text{LOS}} + k r/D}{1 + r/D} \right). \tag{2}
\]

**2.2 Deprojection of the Jets**

With the observed projected angular extension in the sky of the straight part of the Z-shape, \( \Theta_{\text{jet}} \), and the known distance \( D \) of the galaxy we can determine the angle \( \theta_{\text{LOS}} \) between the pre- and post-merger jets, provided we know the radius \( r \) where the jet is bent. Fig. 4 shows the situation for orientation a (\( \delta_{\text{LOS}} < \delta_{\text{jet}} \)) of Fig. 2 projected in a plane perpendicular to the merger plane and containing both the LOS and z-axis. Because \( \varphi \) is assumed to be 0, also the pre-merger jet lies in this plane and the wings are perpendicular to the paper plane. As in Fig. 2 the angles \( \delta \) and \( \theta \) in Fig. 3 denote the angle to the merger plane and z-axis respectively.
and hence for their sum along the $z$-axis in the limit that the distance to the galaxy is much larger than the radius of the rotation stream:

$$y_z = y_a + y_r = 2r \left( k \frac{\tan \delta_{\text{LOS}} - k (r/D)^2}{1 - (r/D)^2} \right)$$

$$\xrightarrow{D \gg r} 2r (k - \tan \delta_{\text{LOS}}).$$

Finally, after projecting $y_z$ into the plane of sky we obtain for the projected lateral offset of the ridges

$$y_p = D \tan \Theta_p = y_z \cos \delta_{\text{LOS}} = 2r \frac{\sin(\delta_{\text{jet}} - \delta_{\text{LOS}})}{\cos \delta_{\text{jet}}}.$$  \(\text{(4)}\)

Proceeding in the same way we obtain for the other possible orientations:

**Orientation b**: (dashed green/light-grey lobes) Like a, with the difference of the angles $\delta_{\text{jet}}$ and $\delta_{\text{LOS}}$ changing sign:

$$y_p = 2r \frac{\sin(\delta_{\text{LOS}} - \delta_{\text{jet}})}{\cos \delta_{\text{jet}}}.$$  \(\text{(5)}\)

**Orientation c**: (solid red/grey lobes) In notation of Fig. 4 like orientation b with the sign of $\delta_{\text{jet}}$ that changed so that in the following expression the angle varies in the range $0 < \delta_{\text{jet}} < 90^\circ$:

$$y_p = 2r \frac{\sin(\delta_{\text{LOS}} + \delta_{\text{jet}})}{\cos \delta_{\text{jet}}}.$$  \(\text{(6)}\)

As we pointed out in Sect. 2.1 we expect $\delta_{\text{LOS}}$ to be small because the post-merger jet is lying close to the plane of sky and $\delta_{\text{jet}}$ is small because the intrinsic angle between both jets is expected to be large. The latter is larger than zero though, because otherwise we could not observe the offset of the wings.

3 APPLICATION ON NGC 326 AND 3C 52

In this section we apply the results obtained above on the two observed Z-shaped XRGs to derive limits for the bending radius and to find the possible orientations. Afterwards we will check whether the jet can still be bent into the wings at the obtained distances.

3.1 Bending radius and orientation

Given the radius $r$ for the rotation field we can solve the above Eqs. 4 to 6 for $\delta_{\text{LOS}}$ and plot it in dependency of $\delta_{\text{jet}}$ in order to find the most likely orientation that minimizes both angles. The expressions we get are

$$\delta_{\text{LOS}} = \begin{cases} 
\delta_{\text{jet}} - \sin^{-1} \left( \frac{y_p}{2r \cos \delta_{\text{jet}}} \right), & \text{orientation } a \\
\delta_{\text{jet}} + \sin^{-1} \left( \frac{y_p}{2r \cos \delta_{\text{jet}}} \right), & \text{orientation } b \\
-\delta_{\text{jet}} + \sin^{-1} \left( \frac{y_p}{2r \cos \delta_{\text{jet}}} \right), & \text{orientation } c.
\end{cases}$$  \(\text{(7)}\)

The lateral offset $y_p$ of the ridges we take from observations of NGC 326 and 3C 52.

**NGC 326**: The distance to this source is about 160 Mpc. Therefore the projected angular size of the middle part of the ‘Z’, $\Theta_p = 20''$, translates into a projected length of about $y_p = 16 \text{kpc}$. Schiminovich et al. (1994) and Charmandaris et al. (2000) have detected dense clouds that contain both H I and molecular gas in Cen A. With an assumed distance of $\sim 3.5 \text{Mpc}$ to Cen A they locate the gas at a radius of about 10 kpc to the center. If we use this as the radius $r$ of the rotation field and plot $\delta_{\text{LOS}}$ in dependency of $\delta_{\text{jet}}$ (Eq. 7) we get the thin curves in Fig. 4. Again the dotted blue/dark-grey line represents the solutions for orientation a, the dashed green/light-grey line for b and the solid red/grey line for c. Because the intrinsic angle is expected to be larger than $\sim 60^\circ$, $\delta_{\text{jet}}$ is less than 30$^\circ$ (left from the shaded area). This limit excludes orientation a which has a minimum of about $\delta_{\text{jet}} = 38^\circ$. The smallest pair of angles in configuration b is 0$^\circ$ for $\delta_{\text{jet}}$ and $\delta_{\text{LOS}} \approx 53^\circ$. Such a large angle violates the condition that primary lobes have to be close to the plane of sky in order to detect an X-shape (region below the shaded area). Hence also this orientation is ruled out and the only remaining possibility is c, where the LOS and the approaching part of the jet are in different hemispheres relative to the post-merger jet. To minimize both angles we get $\delta_{\text{LOS}} = \delta_{\text{jet}} \approx 23.6^\circ$, with not too much range left for them on curve c, if we assume the shaded areas outside the inner rectangle as not permitted. Being pushed to the limit for a radius of 10 kpc, the situation is much less restrictive if we allow for a larger radius. The thick curves in Fig. 4 show the results if the jet is bent in a distance of $r = 30 \text{kpc}$. On branch c both angles are much smaller, with an upper limit of about 15$^\circ$ for $\delta_{\text{LOS}}$. For the larger radius also the other orientations a and b are possible. These two branches appear in the allowed, not-shaded region of Fig. 4 only for $r \geq 14 \text{kpc}$.

**3C 52**: For 3C 52, in a distance of about 1 Gpc, with $\Theta_p = 10''$ the projected offset of the wings is $y_p = 50 \text{kpc}$. This is five times the length of the assumed radius of 10 kpc. But for Eq. 7 to have a solution, the argument of $\sin^{-1}$ has to be less than 1 ($\delta_{\text{jet}}$ varies in a range where the cosine is

![Figure 4. For NGC 326 the angle of the LOS to the merger plane, $\delta_{\text{LOS}}$, is plotted versus the angle $\delta_{\text{jet}}$ between this plane and the secondary lobes, with the bending radius $r$ as parameter. Colors (grey-shades) of the lines refer to the different orientations. In the shaded area both or one angle becomes too large as to fulfill the condition of the primary lobes being close to the plane of sky and the angle between both pairs of lobes to be large.](image-url)
positive), leaving us with the condition
\[
\cos \delta_{\text{jet}} \leq \frac{2r}{y_0}.
\]
For \( r = 10 \, \text{kpc} \) this is fulfilled only if \( \delta_{\text{jet}} \) is larger than 66°, in contradiction with the intrinsic angle between the jet-pairs to be large. So for this small radius none of the orientations is within the allowed rectangle of Fig. 5. Only for \( r \) larger than \( y_0/2 = 25 \, \text{kpc} \) the full range between 0° and 90° becomes mathematically possible for \( \delta_{\text{jet}} \). For this radius the matching angles of the LOS are too large and none of the orientations provides a satisfying solution, see the thin lines in Fig. 5. A larger bending radius can solve the problem again. If we gradually increase the radius, first branch c offers physically reasonable results for both angles \( (r = 24 \, \text{kpc}) \) before the other two branches enter the allowed region for \( r > 44 \, \text{kpc} \). The thick lines in Fig. 5 show the results for \( r = 75 \, \text{kpc} \), with all orientations being possible.

These results show that the bending of the lobes into the wings occurs already much earlier during the merger in distances of more than 20 to maybe even 100 kpc. The smaller the radius is, the more likely the jets have orientation c relative to us, i.e. the receding pre-merger jet and the LOS are in the same hemisphere that is defined by the post-merger jet (axis of orbital angular momentum) as polar axis.

3.2 Bending the jet

If the bending of the jet happens at the distances suggested above, we have to verify that the rotating stream is able to exert a large enough pressure on the jet at these radii to bend it into Z-shape as it has been shown by C-KBW for a radius of 10 kpc. The bending of the jet is described by Euler’s equation, which for a steady state flow reads
\[
\rho_{\text{jet}}(v_{\text{jet}} \nabla) v_{\text{jet}} = -\nabla P_{\text{ISM}},
\]
with the gradient of the ram pressure of the ISM being applied transverse to the beam (O’Donoghue et al. 1993). The velocity of the jet is assumed to change by order of itself over the bending scale \( l_{\text{bend}} \), so that the left hand side of the equation can be written as \( \rho_{\text{jet}}v_{\text{jet}}^2/l_{\text{bend}} \). As O’Donoghue et al. point out a pressure gradient that provides a centripetal acceleration \( v_{\text{jet}}^2/l_{\text{bend}} \) is the result for the left hand side of Eq. 5. The pressure gradient due to ram pressure on the right hand side, \( \nabla P_{\text{ISM}} \), can be approximated by \( \rho_{\text{ISM}}v_{\text{ISM}}^2/l_{\text{press}} \), if \( v_{\text{ISM}} \) is the relative velocity between the ISM and the galaxy, i.e. the rotation velocity. \( l_{\text{press}} \) is the length scale over which the ISM exerts the ram pressure on the jet and is taken to be the radius of the jet \( (R_{\text{jet}}) \) at the bending point \( (r) \). Hence we can rewrite Euler’s equation in the approximation for jet flows as
\[
\rho_{\text{jet}}v_{\text{jet}}^2/l_{\text{bend}} = \rho_{\text{ISM}}v_{\text{ISM}}^2/l_{\text{press}},
\]
Assuming that the clouds in Cen A represent the properties of the ISM reasonably well the following reference values can be used: \( n_{\text{ISM}} = \rho_{\text{ISM}}/(1.4 m_p) = 0.1 \, \text{cm}^{-3} \) and \( v_{\text{ISM}} = 100 \, \text{km/s} \), with \( l_{\text{press}} = R_{\text{jet}} \sim 1 \, \text{kpc} \). The jet is assumed to be semirelativistic \( (v_{\text{jet}} = 10^2 \, \text{km/s}) \) and made of ordinary proton-electron plasma that is bent over a scale of \( l_{\text{bend}} \). Thus for the density of a jet that is bent into Z-shape by ram pressure a density of \( n_{\text{jet}} = 10^{-6} \, \text{cm}^{-3} \) is obtained.

Now we have to scale up the values obtained at \( r_1 = 10 \, \text{kpc} \) to larger distances \( r_2 \) such that Eq. 5 is still fulfilled. In the following the additional indices 1 and 2 refer to the quantities in distance \( r_1 \) and \( r_2 \) respectively. If the half-opening angle of the jet is \( \theta \), then its spherical surface perpendicular to the direction of propagation in a distance \( r \) is \( A = 2\pi r^2(1 - \cos \theta) \). Taking the flux of momentum along the jet \( \rho_{\text{jet}}v_{\text{jet}}^2 A \) to be constant we find
\[
\rho_{\text{jet}}v_{\text{jet}}^2 = \rho_{\text{jet}}v_{\text{jet}}^2 \left( \frac{r_1}{r_2} \right)^2.
\]
With this expression, Eq. 5, the relation \( R_{\text{jet}} = R_{\text{jet}}r_2/r_1 \) and the assumption that \( l_{\text{bend}} \) scales linearly with \( r \) we finally obtain for the density at \( r_2 \)
\[
\rho_{\text{ISM}_2} = \rho_{\text{ISM}_1} \left( \frac{r_1}{r_2} \right)^2 \left( \frac{v_{\text{ISM}_1}}{v_{\text{ISM}_2}} \right)^2.
\]
Hence, to be able to bend the jet in, say \( r_2 = 50 \, \text{kpc} \), the density of the ISM can be 25 times less than at \( r_1 = 10 \, \text{kpc} \). For an annulus with a width from 50 to 60 kpc and of 10 kpc height that density corresponds to a total mass of \( \sim 3.4 \times 10^7 \, M_\odot \). For a velocity of about 200 km/s, as has been observed in such distances (see Sect. 6) the mass is reduced by another factor of four, so that it is less than \( 10^7 \, M_\odot \). At \( r_1 \) the mass in a ring with inner and outer radius 7.5 and 12.5 kpc respectively and a height of 5 kpc is \( \sim 4 \times 10^6 \, M_\odot \). Thus about the same mass that is required in a rotating stream with radius 10 kpc to bend the jet into a Z-shape is sufficient to bend the jet at much larger radii. The required mass and velocity at such distances is in agreement with observations (see next section). Hence our results show that the ram pressure of the rotating gas in a distance of \( \sim 50 \, \text{kpc} \) is indeed strong enough to bend the jet in Z-shape, as is required by the geometrical arguments above.
4 DISCUSSION

4.1 Geometry and dynamics of the jet

In the previous sections we showed that the bending of the pre-merger jet into Z-shape, as proposed by [G-KBW] within the merger model, must happen on distances larger than the 10 kpc that they have suggested. Because the half-thickness of the rotating gas stream will not be larger than its radius, it has to pass through the polar regions of the primary galaxy in order to bend the jet and thus pre- and post-merger jets are approximately perpendicular to each other. This corresponds to the maximum of the distribution of the intrinsic angle ($\theta_{\text{jet}} = 90^\circ$) between both pairs of lobes in XRGs, if the directions of their propagation are uncorrelated. But this is exactly what we expect in the merger model for XRGs, if the spin of the post-merger SMBH is dominated by the orbital angular momentum of the binary, as pointed out in Sect. 4.1 In ZRGs a larger bending radius is in favour of a larger angle $\theta_{\text{jet}}$ between the jets. For example $y_p = 50$ kpc has been observed in 3C 52. Trying to minimize the the half-height $h$ for $r = 10$ kpc, i.e. maximizing $\theta_{\text{jet}}$, we obtain with orientation a $h = y_p / 2 = 2.5r$ at $\theta_{\text{jet}} = 21.8^\circ$ and $\delta_{\text{LOS}} = 0$. In case b there is no solution at all for $y_p \geq 2r$ and for c we get $h = 2.3r$ at $\theta_{\text{jet}} = 25.6^\circ$ and $\delta_{\text{LOS}} = 23.6^\circ$. This is in direct contradiction with a slim gas stream and with the assumption of a large angle between both jet pairs and could be solved with a larger bending radius (Sect. 4.1).

As [G-KBW] estimated, the ram pressure of the rotation field at 10 kpc radius is strong enough to bend a jet with power close to the FR I/II transition into Z-symmetry. A stronger jet would not be much deflected by the rotating gas-stream. Because the wings are in the plane of sky and extend almost perpendicular from the post-merger jet, the pre-merger jet would also have to be close to the plane of sky and hence distinguishable from the primary jet, as we pointed out at the end of Sect. 4.1. However, this has not been observed and thus also the appearance and morphology of the source argue for weaker jets which can be deflected by a large angle. But the jet should not be too weak as well, because then it would be just dragged along with the circular gas stream and hence have a maximum projected extension of the bending radius. Depending on the angle of the LOS to the merger plane we might see the curvatures of the wings following the circular motion and exhibiting inversion symmetry relative to the center as depicted in Fig. 2 (of course jets deflected at smaller angles also show inversion symmetry, but they can more easily deviate from that due to interaction with the ambient medium). In case of NGC 326 and 3C 52 this means a bending radius of at least 50 and 100 kpc respectively. It is more likely that a weak jet would be bent at smaller radii by the inspiralling gas stream, where the jet has a larger power and hence would probably be deflected but not dragged along with the rotational motion. In Sect. 4.2 we showed that a gas stream with a similar mass content as that required for bending at 10 kpc is able to bend the same jet at larger distances of about 50 kpc. After spiralling further inside to smaller radii the secondary galaxy will have suffered more stripping of material and the gas stream becomes weaker while the jet becomes stronger. The requirements for the stream at 50 kpc are in good agreement with observations (Sect. 4.2). Hence the conclusion by [G-KBW] that the bending of jets into Z-shape happens at a jet-power close to the FR I/II transition holds also at larger radii.

4.2 Evidence for the required streams

In the present model we assume XRGs and ZRGs to be merger products. As such it is expected that the secondary galaxy, while spiralling inwards, induces a stream of gas and dust on scales of tens of kpc in the primary galaxy. This stream is due to matter of the primary galaxy dragged along by the secondary as well as matter stripped off from the secondary galaxy. Now looking for such streams in other sources shows that they have been observed in various objects. These streams are always related to a merger between two galaxies. This is also in very good agreement with numerical simulations of mergers which produce tidal tails and streams with the properties required in our model ($\rho, v, r$) and hence lends strong support to it. In the following we compile some information of these sources. We use $H_0 = 70$ km/s/Mpc and scaled the values from the cited papers accordingly. A summary is given in Table 1.

Recent H i observations of M 31 by [Thilker et al. 2004] show a circumgalactic cloud population in ~ 50 kpc distance. These clouds are moving with a velocity component along the LOS of $v_{\text{sys}} \pm 128$ km/s, matching the velocity extent of the disk of M 31. Though the H i content of the halo cloud population is estimated to be only ~ $3 \times 10^7 M_\odot$, it might trace more substantial amounts of ionized gas and dark matter. As an obvious source of the high-velocity H i gas the authors give tidal stripping from mergers in agreement with [Brown et al. 2003], who relate the young halo to a major merger or several minor mergers.

[Braun et al. 2003] conducted a H i survey and found significant positional offsets exceeding 10 kpc in some of the sources, which they attribute to tidal interaction. While the mean observed offset of H i is about 66 kpc, in NGC 1161 H i is observed in 110 kpc distance to the center at speeds that differ by ~ 200 km/s from the systemic velocity. The H i mass is estimated to be about $1.8 \times 10^9 M_\odot$.

The H i detected by [van Gorkom et al. 1985] in NGC 1052, an active elliptical galaxy, is distributed in a disk that extends 20–25 kpc along the minor axis and is seen almost edge on. The gas has a circular velocity of ~ 200 km/s that is roughly constant with radius. The H i mass is about $5.7 \times 10^9 M_\odot$ and shows an outer structure that resembles tidal tails, which [van Gorkom et al.] attribute to a merger about $10^9$ yr ago.

In another early type galaxy, IC 5063 which has a Seyfert 2 nucleus, [Morganti et al. 1994] detect H i that to first order is distributed in disk of about 28 kpc radius. This disk is oriented very similar to a system of dust lanes and in projection rotates at 240 km/s with an H i mass of $4.2 \times 10^9 M_\odot$. Optical data from previous observations (e.g., [Danziger et al. 1981]) revealed ionized gas that also lies in a disk, which is extending to ~ 14.4 kpc. The faint structures in the outer regions could be tidal arms and the origin of H i is most likely a merger between spiral galaxies as in the other sources.

Among the five elliptical galaxies that [Oosterloo et al. 2002] observed they detected $2.3 \times 10^9 M_\odot$ of H i in NGC 3108 that is distributed in a disk-like structure perpendicular to the optical major axis of the galaxy and extends

Orientation and size of the ‘Z’ in XRGs
to $\sim 30$ kpc. They assume an inclination of $70^\circ$ and thus obtain for the rotation velocity $290$ km/s, which appears to be constant from $\sim 1$ kpc to the very outer regions. Within the central 1' the disk seems to have a hole that is filled by a disk seen in emission from ionized gas. While the boxy outer isophotes indicate that also NGC 3108 has undergone a major merger, the regular and settled appearance of the disk suggest that it happened some 10$^9$ yr ago.

Cen A is a giant elliptical galaxy with an active nucleus that shows strong radio lobes on both sides of a dust lane which is aligned with the minor axis (Clarke et al. 1992) and a warped gaseous disk which is seen in optical and H$\alpha$ emission (Dufrane et al. 1973; van Gorkom et al. 1994). Schiminovich et al. (1994) find the H$\alpha$ morphology to be closely correlated with diffuse shells seen in the optical range (Malin et al. 1983) and estimate the total mass in the shells to be $\sim 1.5 \times 10^9$ $M_\odot$. The position-velocity (PV) plot of H$\alpha$ in the shells is well fitted by a single ring with uniform rotation velocity ($\sim 250$ km/s) and the rotation axis being roughly perpendicular to that of the inner H$\alpha$ disk. The rotation curve is flat out to 15', what corresponds to a radius of 34 kpc for $D = 8$ Mpc, using a redshift of $z = 0.001825$ (note that Schiminovich et al. used $D = 3.5$ Mpc, and hence $r \sim 10$ kpc, what we initially used as bending radius in Sect. 3.4.1). As possible explanation for the misalignment between the rotation axis of the H$\alpha$ in the shells and the disk they suggest a merger which is not proceeding in the plane of Cen A, and differential precession of the stripped material. Later Charmandaris et al. (2004) suggested that the morphology of the shells is a combination of both, phase wrapping of tidal debris on nearly radial orbits (Quinn 1984) and spatial wrapping of matter in thin disks for mergers with large angular momentum (Dupraz & Combes 1987; Hernquist & Quinn 1988). They also detect CO emission in the shells and associate it with the H$\alpha$ gas which shows the same velocity signatures and deduce a H$_2$-mass of $4.3 \times 10^7$ $M_\odot$.

In NGC 5266, a bright E4 galaxy, Morganti et al. (1997) find H$\alpha$ gas distributed in two perpendicular disks. The inner disk is aligned with the dust lane and fills the hole of $\sim 2'$ diameter of the outer disk, which extends to 4' (51 kpc). For the rotation velocity of this disk they obtain $270$ km/s, which is constant in radius, and for the total H$\alpha$ mass $1.2 \times 10^9$ $M_\odot$. They point out that the H$\alpha$ distribution is similar to that observed in Cen A, with most of H$\alpha$ being associated with the dust lane but a different kinematical behaviour at larger distances and forming a ring that is roughly perpendicular to the dust lane. This is unlike in most polar-ring and dust-lane galaxies. The outer parts of H$\alpha$, extending to $\sim 100$ kpc, could be a settled ring but are rather interpreted as tidal tails that formed during a merger of two gas-rich spiral galaxies. Numerical simulations by Hibbard & Mihos (1995) (see later in this section) have shown that after gas piling up in the center and fuelling a star burst, the fraction that remains at larger distances in tidal tails will settle in a disk or a ring, depending on the initial conditions. Earlier observations in the optical range indicate that the kinematic axes of stars and gas are orthogonal, with the gas in the dust lane rotating about the optical major axis (Caldwell 1984). Goudfrooij et al. (1994) could show that ionized gas lies in a ring that is clearly associated with the dust ring detected. In CO observations Saxe & Galletta (1993) found that the molecular gas is also distributed in a ring that is co-rotating with the ionized gas at velocities of $270 - 300$ km/s within 1' ($\sim 13$ kpc) and has a mass in H$_2$ of $2.7 \times 10^9$ $M_\odot$.

Recently Swaters & Rubin (2003) observed the polar ring galaxy NGC 4650A and found the velocities of both, stars and gas in the polar ring component to be closely correlated. The ring is seen close to edge on and rotates close to its outer parts ($\sim 10$ kpc) with a velocity of 120 km/s. The flatness of the rotation curve suggests that the gas and stars are rather distributed in a disk than a narrow ring. This is supported by the results of Bekki (1998) who simulated a dissipational polar merger of two disk galaxies of about the same mass. In his numerical experiments he could reproduce polar ring galaxies, with the intruding galaxy being transformed into a S0-like host and the victim into a narrow polar ring. As standard model Bekki used $10^{11}$ $M_\odot$ and 10 kpc for the disk mass and radius respectively. These are quite small values and we scaled the model to masses in the range of $10^{11-12}$ $M_\odot$. Then crude estimates of the size, velocity and mass of the polar ring result in the ranges that are required by our model, i.e. 30 - 100 kpc, 100 - 300 km/s and $\sim 1/100 M_{\text{disk}}$, respectively. Bekki notes that he seemed to have failed to reproduce annular polar ring galaxies like NGC 4650A, unless the annular ring component with an apparent hole in the center is a part from the galactic disk, in good agreement with the conjecture by Swaters & Rubin (2003) based on their observations.

In other numerical simulations of mergers Bournaud et al. (2004) compared their results with the kinematics of tidal tails in interacting galaxies. Their main goal is to distinguish whether apparent massive condensations close to the tips of the tails are real or caused by projection effects. The PV plots can qualitatively distinguish both possibilities: Either the difference between the systemic velocity and the tidal tail increases with position along the tail, reaching a maximum at its end, or it passes through a maximum before it decreases and even turns back to closer positions at smaller speeds, thus following.

### Table 1. Observed masses and properties of rotating gas streams.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\log(M_{\text{HI}}/M_\odot)$</th>
<th>$r$ (kpc)</th>
<th>$v$ (km/s)</th>
<th>$D$ (Mpc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M 31</td>
<td>7.5 - 7.9$^{(a)}$</td>
<td>50</td>
<td>$+128^{(c)}$</td>
<td>0.77</td>
</tr>
<tr>
<td>NGC 1161</td>
<td>9.3</td>
<td>110</td>
<td>200</td>
<td>28</td>
</tr>
<tr>
<td>NGC 1052</td>
<td>8.8</td>
<td>20 - 25</td>
<td>200</td>
<td>21</td>
</tr>
<tr>
<td>IC 5063</td>
<td>9.6</td>
<td>28</td>
<td>240</td>
<td>48.6</td>
</tr>
<tr>
<td>NGC 3108</td>
<td>9.4</td>
<td>30</td>
<td>200</td>
<td>38</td>
</tr>
<tr>
<td>Cen A</td>
<td>8.2</td>
<td>34</td>
<td>250</td>
<td>8</td>
</tr>
<tr>
<td>NGC 5266</td>
<td>10.1$^{(b)}$</td>
<td>51 - 100</td>
<td>270</td>
<td>44</td>
</tr>
<tr>
<td>NGC 4650A</td>
<td>10.1$^{(c)}$</td>
<td>10</td>
<td>120</td>
<td>41</td>
</tr>
<tr>
<td>IC 1182</td>
<td>10.3</td>
<td>60</td>
<td>100</td>
<td>146</td>
</tr>
<tr>
<td>Arp 105</td>
<td>9.8</td>
<td>100</td>
<td>200</td>
<td>125</td>
</tr>
<tr>
<td>NGC 7252</td>
<td>9.6</td>
<td>60</td>
<td>100</td>
<td>67</td>
</tr>
</tbody>
</table>

$H_0 = 70$ km/s/Mpc has been used throughout. $M_{\text{HI}}$ is the H$\alpha$ mass in disks or streams. This gas has been observed in distance $r$ to the center and is moving at circular velocities $v$. Only for M 31 the velocity has not been deprojected. $^{(a)}$ Mass of the halo cloud population, possibly tracing more substantial amounts of ionized gas and dark matter. $^{(b)}$ Total H$\alpha$ mass. $^{(c)}$ Luminous mass in polar structure. For details and references see text.
a loop. We are more interested in the latter case which can give us information about the azimuthal component of the velocity in the tail, that we assume to be edge on. The matter in the tail is not streaming along its spatial extension and also has a velocity component perpendicular to the tangential one. As the velocity component aligned with the LOS is measured along the tail with increasing distance to the center, the velocity increases. Before the tip is reached the velocity assumes a maximum when the velocity in the tail is aligned with the LOS. As the observer moves on to the tip where only the azimuthal component is aligned with the LOS, the velocity decreases. Comparison with observations show that IC 1182 and the northern tail of Arp 105 fall in this category with a circular velocity of \( \sim 200 \text{ km s}^{-1} \) at \( \sim 100 \text{kpc} \) from the center and \( \sim 100 \text{ km s}^{-1} \) at \( \sim 100 \text{kpc} \) respectively. The corresponding \( \text{H}\text{i} \) mass at the end of the tails they estimate to be about \( 1.8 \times 10^{9} \text{ M}_{\odot} \) and \( 6.5 \times 10^{9} \text{ M}_{\odot} \) respectively.

NGC 7252 is a late stage merger of two gas-rich disk galaxies (e.g., Dupraz et al. 1990; Wang et al. 1992; Hibbard et al. 1994). The morphology and kinematical properties of the tidal tails have been tried to be reproduced with numerical simulations by Hibbard & Mihos (1995). The PV plot in a previous paper by Hibbard et al. (1994) shows that the tails have a maximum velocity along the LOS of 100 km/s at \( \sim 60 \text{kpc} \) before turning back in a loop in the PV-plane. The \( \text{H}\text{i} \) mass in the tails is estimated to be \( \sim 4 \times 10^{9} \text{ M}_{\odot} \). The best-fit model of Hibbard & Mihos (1992) succeeds in reproducing both the observed spatial morphology and the velocity structure of the tails. By the time the simulated merger fits best the observations (\( \sim 8.3 \times 10^{8} \text{ yr} \)) about \( 4 \times 10^{9} \text{ M}_{\odot} \) \( \text{H}\text{i} \) is still in the tails, half of which will fall back to radii \( \lesssim 20 \text{kpc} \) during the next \( 4.3 \times 10^{9} \text{ yr} \). We used the angular momentum – radius plot to compute the circular velocity of the matter falling back to 35 kpc from the range between 65 and 130 kpc and obtain a velocity range from 100 to 200 km/s respectively. Hence for a long time a stream of gas strong enough to bend the jet is maintained in a distance of about 35 kpc. Some of the falling back material will form loops or shells and other structures. In more recent simulations Mihos et al. (1998) examined the effect of dark matter halo potentials on the morphology and kinematics of tidal tails. They basically confirm the previous results from Hibbard & Mihos (1995) which are relevant for our purposes. From the mass of the initial \( \text{H}\text{i} \) disk 10—20% and about 15—20% of the initial total disk mass ends as stellar mass in the tidal tails. Scaled to the Milky Way this is about \( 6.6 \times 10^{9} \) and \( 7.2 \times 10^{9} \text{ M}_{\odot} \) respectively that circulates at velocities of 220 km/s at distances more than 100 kpc around the center.

Both, the observations of galaxies showing signatures of mergers about \( 10^{9} \text{ yr} \) ago, and simulations of merging galaxies are in good agreement with our model. With the properties shown in Table I the merger induced gas stream is able to bend a jet with power close to the FR I/II transition into \( Z \)-shape on distances larger than 30 kpc.

5 CONCLUSIONS

In the present article we are investigating in the possible orientation and geometry of \( Z \)-shaped radio galaxies (ZRGs).

The formation of objects of this class has been explained by G-KBW within the framework of a merger model. As the secondary galaxy spirals in towards the common center of mass it generates a rotational velocity field of gas and dust in its wake that is made up by matter stripped off from the secondary galaxy and matter dragged along from the ambient medium of the primary galaxy. If the trajectory passes through the polar region of the primary galaxy, its jet can be bent into a \( Z \)-symmetric shape, depending on the relative pressure between the gas stream and the jet. Thus for these sources the spin of the primary SMBH and the orbital angular momentum \( \textbf{L}_\text{orb} \) of the binary are necessarily roughly perpendicular to each other. Provided that the spin of the post-merger SMBH is dominated by \( \textbf{L}_\text{orb} \) and that jets are aligned with the spin of the SMBH at their base, consequently the pre- and post-merger jets will also be perpendicular to each other. While this should be true for every ZRG, this holds for XRGs only on average since the direction of the \( \textbf{L}_\text{orb} \) and the pre-merger spin of the SMBH are uncorrelated, as explained in Sect. 2.1 (Rottmann 2001; Zier & Biermann 2001, 2002). We used this argument for large angles between the jet pairs and the assumption that the post-merger lobes are close to the plane of sky, because they are similarly luminous, to deproject the jets with respect to the LOS. Applied to the ZRGs NGC 326 and 3C 52 our results showed that to fulfill both conditions the bending of the jet must happen on scales between about 30 and 100 kpc. One important result is that the possibility to see the source at one of the possible three orientations, indicated in Fig. 2, depends on the bending radius (Sect. 3). To maintain a large angle between the jet pairs and a primary jet close to the plain of sky we used the following limits for the angles: \( \theta_{\text{jet}} = 90^\circ - \delta_{\text{jet}} > 60^\circ \) and \( \delta_{\text{LOS}} < 35^\circ \), which we think to be quite conservative. For very small bending radii \( r \) no solution is in the allowed range (white rectangle in Figs. 4 and 5). As we increase \( r \) first orientation \( c \), where the LOS and the approaching part of the pre-merger jet are in different hemispheres that are defined by the post-merger jet as polar axis, appears in the allowed region for \( r \gtrsim y_p/2 \) (i.e. 8 and 25 kpc for NGC 326 and 3C 52 respectively). If we further increase \( r \) both the other orientations also appear in the allowed rectangle at roughly the same radius \( r \gtrsim y_p \sqrt{3}/2 \) (14 and 44 kpc for NGC 326 and 3C 52 respectively). Knowing the correct orientation we also know the sense of rotation, i.e. \( \textbf{L}_\text{orb} \), and consequently the direction of the spin of the post-merger SMBH (Chirvase 2003; Zier & Biermann 2002; Biermann et al. 2003). In future work this could be compared with the spin inferred from circular polarization measurements at cm-wavelengths, as has been discussed by Enßlin (2003) and suggested by G-KBW.

The radius of the bending will depend on the relative pressure between the jet and the gas stream. In Sect. 3.2 we showed that for a jet with a power close to the FR I/II transition this happens on scales of 50 kpc, in agreement with the results from the geometrical arguments above. Thus the conclusion by G-KBW that the jet is bent at a power close to the FR I/II transition is also valid at radii in a range of 30 to 100 kpc. In fact in Sect. 3.1 we showed that neither very strong nor weak jets are in agreement with the geometry of ZRGs.

ZRGs can not be explained by the rapid jet reorientation from instabilities in an accretion disk, what is also
considered as one possible formation mechanism of XRGs (Dennett-Thorpe et al. 2002), and might not be easily reconciled with the observed distribution of angles between the jet pairs. Since ZRGs are a subset of XRGs their existence strongly supports the merger model in favour of the accretion model as formation mechanism of XRGs. In this context our result that the angles between both jet pairs have to be large in ZRGs and are large on average in XRGs, as has been observed (Rottmann 2001), further strengthen the merger model.

This in turn will have some impact on the “final parsec problem”, i.e. the conjecture that after a merger of two galaxies the merging of the SMBHs stalls in a distance of about 0.01 to 1 pc (Begelman et al. 1980). At this distance dynamical friction is inefficient and gravitational radiation still unimportant so that slingshot ejection of individual stars provides the only mechanism to extract energy and angular momentum from the binary (Zier & Biermann 2001). If there are no stars with small enough pericenters as to interact with the binary (i.e. loss-cone depletion) the SMBHs are prevented from further merging. But contrary to that the existence of XRGs and ZRGs shows that the binary has merged. In ZRGs they probably merge on timescales of some $10^8$ yr after the bending of the jet in a distance of 50 kpc. While in XRGs the binary could have stalled for a long time on scales of 1 pc, in ZRGs the merger must have been completed after the bending in a time short enough to maintain the rotational gas stream and that we are still able to see the bended lobes, which are fading away and undergo spectral ageing (Rottmann 2001). Thus, in a way, the bending starts a stop watch for the rest of the merger.

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REFERENCES

Begelman M. C., Blandford R. D., Rees M. J., 1980, Nat., 287, 307
Gull S. F., Northover K. J. E., 1973, Nat., 244, 80
Rottmann H., 2001, PhD thesis, University of Bonn