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Real vs. simulated relativistic jets

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Abstract.
Intensive VLBI monitoring programs of jets in AGN are showing the existence of intricate emission patterns, such as upstream motions or slow moving and quasi-stationary componentes trailing superluminal features. Relativistic hydrodynamic and emission simulations of jets are in very good agreement with these observations, proving as a powerful tool for the understanding of the physical processes taking place in the jets of AGN, microquasars and GRBs. These simulations show that the variability of the jet emission is the result of a complex combination of phase motions, viewing angle selection effects, and non-linear interactions between perturbations and the underlying jet and/or ambient medium. Both observations and simulations suggest that shock-in-jet models may be an overly simplistic idealization when interpreting the emission structure observed in actual jets.

1. Introduction

The improvement in the sensitivity and angular resolution of VLBI observations has allowed the study of relativistic jets with unprecedented detail. This advance in the observational techniques has come together with a rapid development of numerical codes capable of computing the hydrodynamics of jets with relativistic velocities and energies. Computation of the emission maps from these models can be used for a direct comparison with observations, providing therefore a powerful tool for the study of these objects.

2. Real jets: observations

During the last decade a significant observational effort has been made to improve our knowledge of the inner jet structure, with special attention to the magnetic field structure and strength, and its possible influence in the jet dynamics. Recent observations (Gabuzda 2003) suggests that the induced transverse magnetic fields are in fact associated with a toroidal component of the jet magnetic field, instead of reordering by shocks. This also leaves room for alternative explanations in which jet components may be associated with kinks in currents originated by the toroidal fields, instead of strong hydrodynamical shocks (Gabuzda 2003).

Recent intensive monitoring programs have allowed the study of the inner jet structure of several sources with the finest time sampling (see e.g., Gómez et al. 2000, 2001; Wehrle et al. 2001; Walker et al. 2001; Marscher et al. 2002; Stirling et al. 2003; Vermeulen et al. 2003). One of the best candidates for such intensive monitoring programs is the radio galaxy 3C 120. This is a one of the closest known extragalactic superluminal sources (z=0.033) and is a powerful emitter of radiation along the whole spectrum.

Monthly 16 epochs of polarimetric 43 GHz VLBA observations of 3C 120 (Gómez et al. 2001) reveal multiple superluminal components with velocities in the rage between 4 and 5.8 $h_{65}^{-1}c$. Model fitting of the u-v is shown in Fig. 1 (*left*). By the end of 1997 the source was observed to flare, followed by the ejection of a new strong superluminal component, soon resolved into several distinct features (*o1*, *o2* and *p* in Fig. 1). These probably do not represent distinct entities but rather correspond to the complexity of the internal brightness distribution, as shown in simulations (Gómez et al. 1997). While subcomponents *o1* and *o2* move with a relatively constant velocity, Fig. 1 shows that component *p* splits into two parts that decelerate and decrease in flux more rapidly than *o1* and *o2* do. By September 1998 a similar split takes place, leading to the appearance of components *m* and *m1*. Two components closer to the core, labeled *r* and *s*, are also observable in Fig. 1. These new components appear in the wake of the main superluminal feature (containing *o1* and *o2*) and present significantly slower (by a factor of ~4) proper motions than any of the other superluminal components detected in 3C 120. Further evidence for slow moving or quasi-stationary components trailing superluminal features has been found by similarly dedicated monitoring programs on other sources (Tingay et al. 2001; Jorstad et al. 2001).

These intensive monitoring program on 3C 120, consisting also of simultaneous observations at 22 GHz, led Gómez et al. (2000) to find a region in the jet of 3C 120 in which superluminal components present variations in the total and polarized flux densities with time scales of months, accompanied by a progressive rotation of the magnetic polarization vector. This was interpreted as due to the interaction of the jet with the external medium or a cloud with properties intermediated of those of the broad and narrow emission-line regions (Gómez et al. 2000). The rotation of the magnetic vector was interpreted

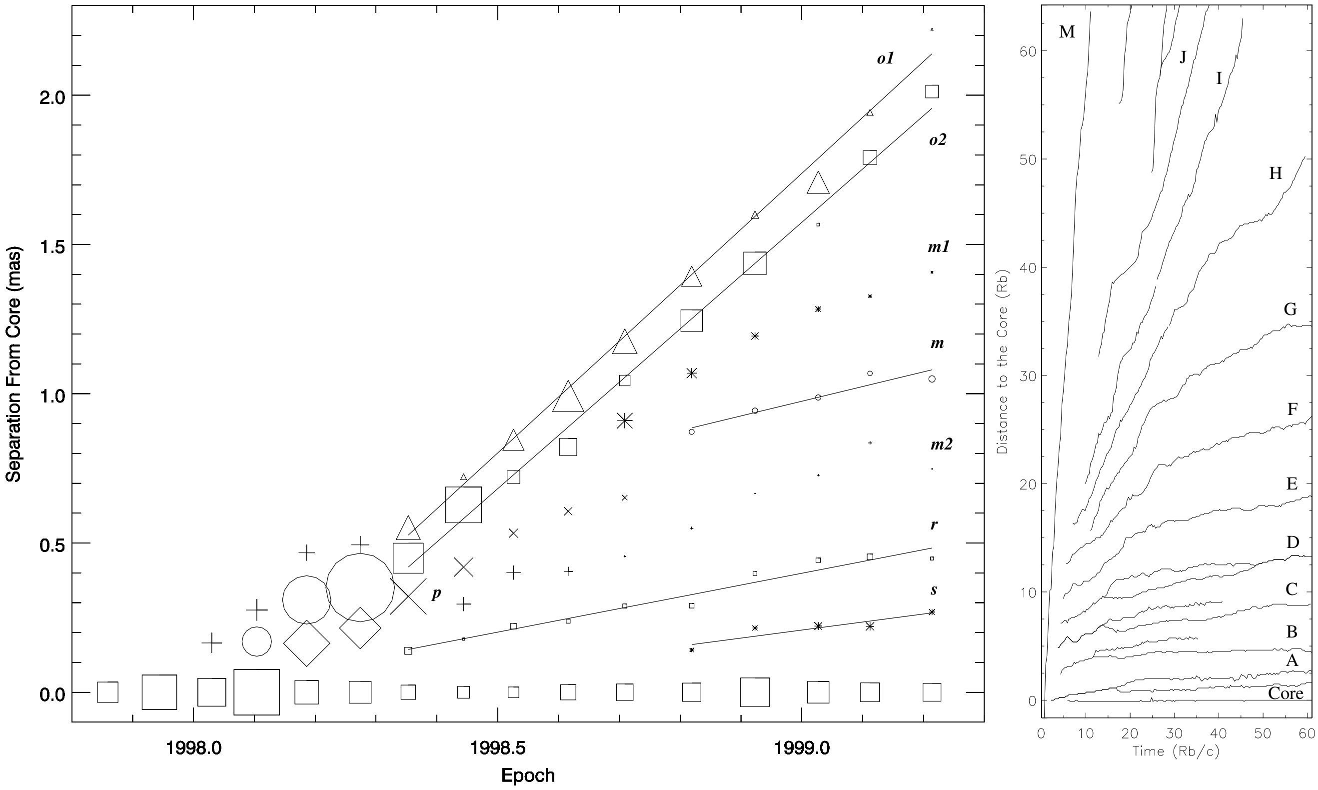

Fig. 1. *Left*: Projected angular distance from the core vs. time for the inner jet features of the jet in 3C 120. The symbol size is proportional to the component's total flux density. Reproduced from Gómez et al. (2001). *Right*: Distance to the core vs. time for the components appearing in a relativistic hydrodynamic and emission simulation (Agudo et al. 2001) of a jet in which a perturbation, associated with the component labeled *M*, has been injected.

by these authors as produced by Faraday rotation of the ionized cloud, the level of which was estimated from the different polarization angles observed at 22 and 43 GHz.

Later VLBA observations at 15, 22, and 43 GHz (see Figs. 2 and 3), confirm the presence of a rotation measure (RM) region at the same location as that reported by Gómez et al. (2000). However, the amount of RM in the region seems to have dropped from $\sim$ 6000 to $\sim$ 3800 rad m^{-2} in about two years. This variability may be expected in the case of being affected by a rapid evolving interaction of the jet with the external medium or cloud. This Faraday screen is also coincident in position with a region of increased jet opacity, as shown in Fig. 4 of Gómez et al. (2000).

Similar interactions between the jet and external medium have been reported for other sources. In Gabuzda et al. (2001), the highly bent structure of the BL Lac object 0735+178 is interpreted as the interaction of the jet with the external medium. Increased RM, coincident with a region of enhanced opacity, is observed at the location where the jet bends by an angle of about 90° in the plane of the sky. In Homan et al. (2003) a jet interaction with the external medium is considered to explain the observed deflection of a superluminal component (labeled *C*4) in its motion along the jet of 3C 279.

Most of our knowledge of the nature of relativistic jets comes from the study of the emission components proper motion and flux evolution. Superluminal components in jets exhibit ballistic motions away from the core, as well as curved paths suggestive of streaming motions along a funnel (e.g., Homan et al. 2001; Lister 2001). Some of these bent jets resemble helical structures in projection, presumably originated by precession of the jet nozzle. Growing evidence suggests that this is actually the case for BL Lac itself, where components are found to be ejected at different position angles, initially moving with ballistic trajectories to later on follow curved paths that are in agreement with a helical jet (Denn, Mutel & Marscher 2000; Stirling et al. 2003; Gabuzda & Cawthorne 2003).

The radio galaxy 3C 120 also presents significant evidence in favor of a jet precession, or at least a change in the direction of the jet nozzle. The images of Fig.2, specially that of the higher resolution at 43 GHz, shows a jet structure in which the knots of emission plot a twisted structure resembling that of a helix in projection. This precessing nature of 3C 120 has also been suggested by studying the changing direction for the direction of ejection of components (Gómez et al. 1998). Further evidence has been found by analyzing the changes in position angle and magnetic field orientation of the superluminal components in their motion along the jet, specially in the inner 2 mas from the core (see Fig. 5 of Gómez et al. 2001).

Other similar evidence for jet precession is being found in an increasing number of sources (e.g., Walker et al. 2001; Lister et al. 2003). Interpretation of this phenomenon, as well as other intricate emission structure variability such as upstream phase motion of jet features (Wehrle et al. 2001), requires a detailed

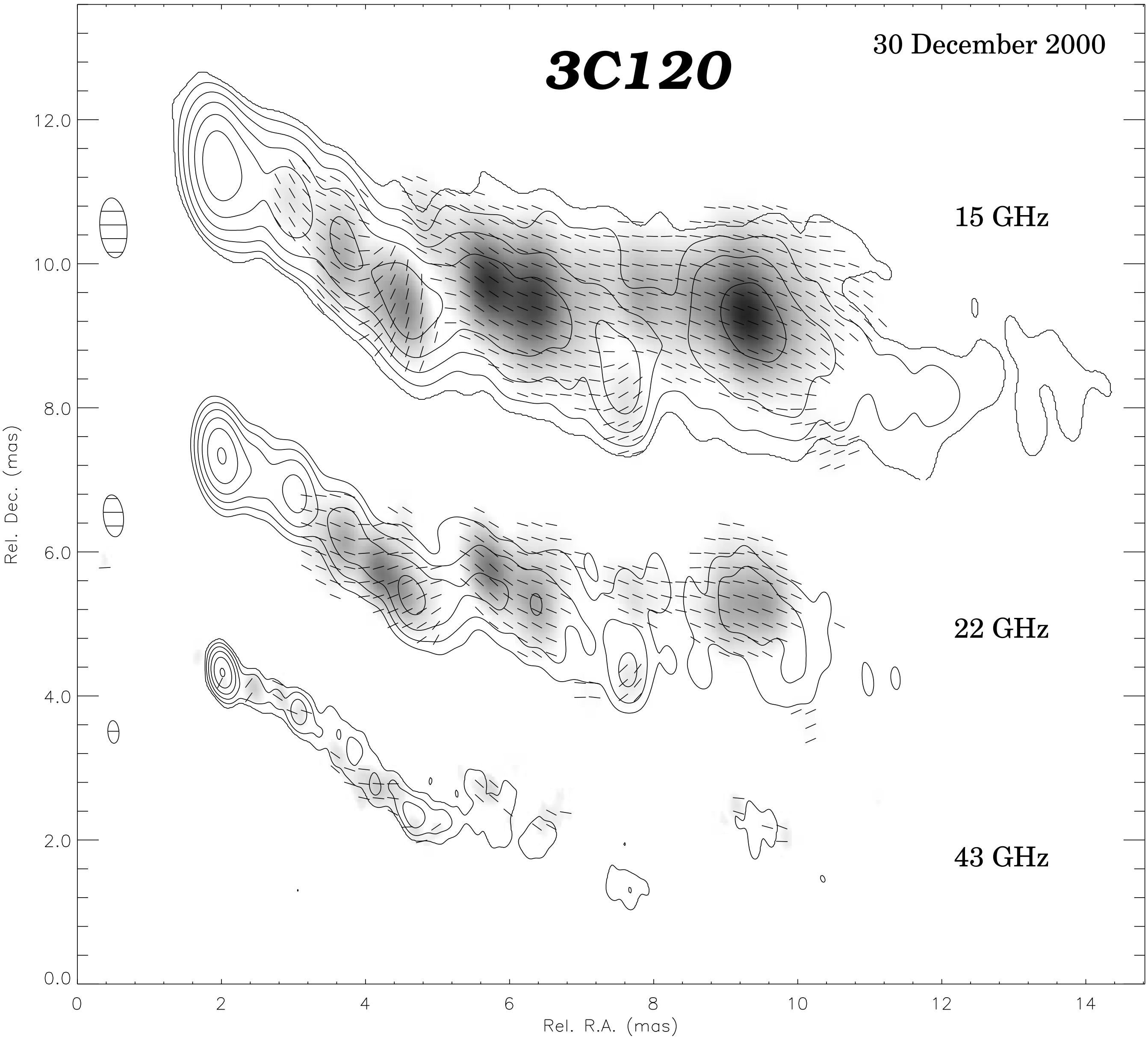

Fig. 2. VLBA images of the radio galaxy 3C 120 for 30 December 2000 at 15 (top), 22 (middle), and 43 GHz (bottom). Total intensity is plotted in contours at common values for the three images of 0.001 (only for 15 GHz), 0.003, 0.009, 0.026, 0.076, 0.222, and 0.647 Jy/beam. Linear gray scale shows the linearly polarized intensity. Bars (of unit length) indicate the direction of the magnetic polarization vector. Convolving beams are plotted to the left of each image.

modeling of the hydrodynamic and emission processes taking place in these relativistic sources.

3. Numerically simulated relativistic jets

The development of modern high resolution techniques in numerical hydrodynamics has allowed the computation of time dependent simulations of relativistic jets (Martí, Müller & Ibáñez 1994; Duncan & Hughes 1994, and review Martí & Müller 1999). These models are capable, for the first time, to study the jet dynamics with unprecedented detail, and under very similar conditions as it is thought are taking place in real sources (that is, strong shocks, relativistic internal energies and bulk flow velocities, etc.). Some of the latest simulations have started to explore three-dimensional relativistic jets (Aloy et al. 2003, and references therein; Hardee et al. 2001; Hughes, Miller & Duncan 2002), magnetized relativistic jets (Komissarov 1999), as well as jet formation and collimation making use of general relativistic magnetohydrodynamic codes (Koide 2003, and references therein; Gammie, McKinney & Tóth 2003; De Villiers & Hawley 2003).

However, the observed emission structure is not just a direct mapping of the jet hydrodynamical variables (pressure, density, velocity). The final radiation reaching our detectors is greatly determined by other several processes, like opacity, particle acceleration, radiative losses, Faraday rotation, and, most importantly, by relativistic effects such as light aberration and light

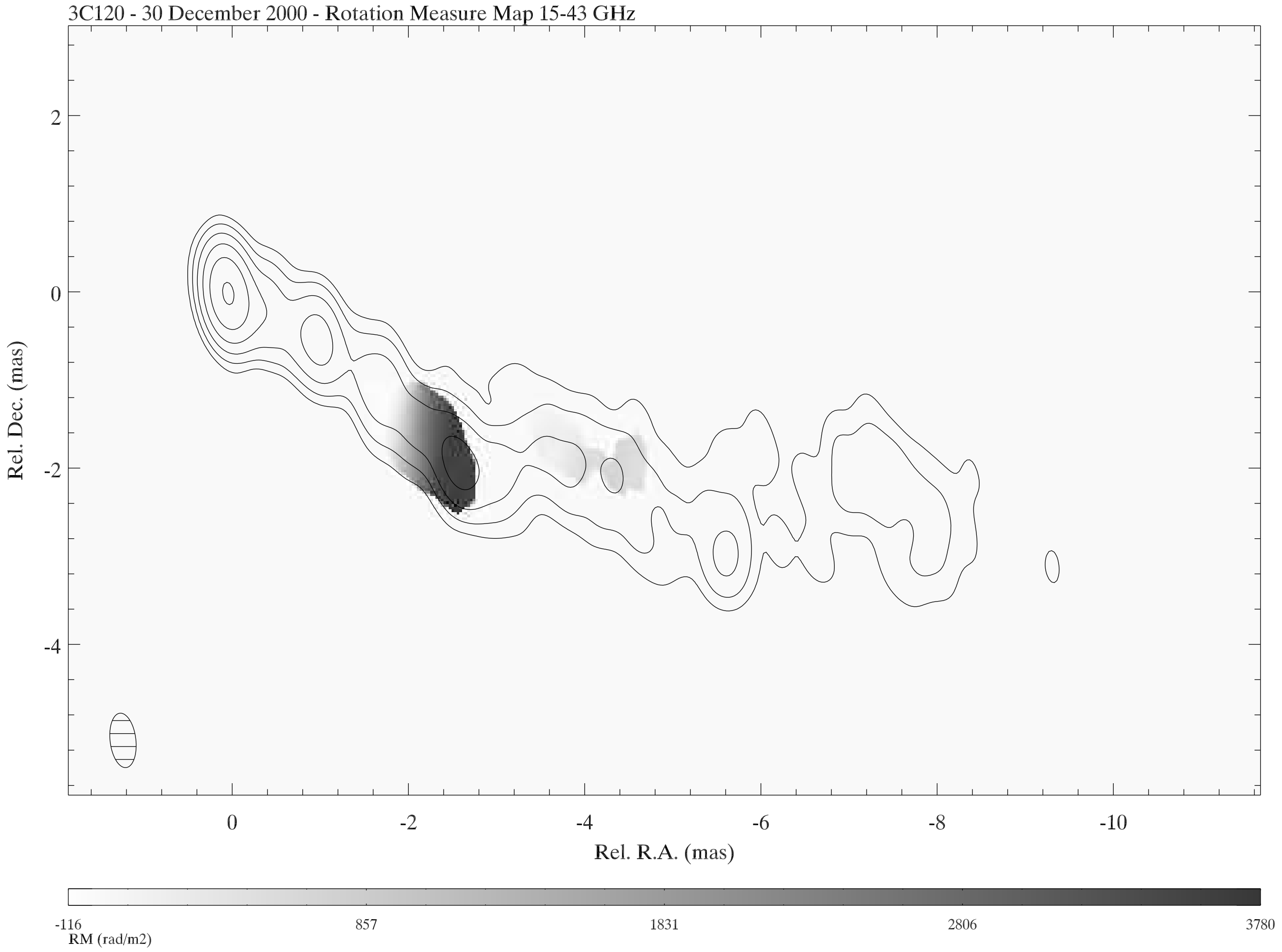

Fig. 3. Rotation measure map (gray scale) for the radio galaxy 3C 120 at 30 December 2000 combining the images shown in Fig.2. Contours show he total intensity image at 22 GHz.

travel time delays. For relativistic speeds (and small viewing angles) time delays can be of such importance as to leave the emission images with no apparent relationship to the hydrodynamical jet structure. Hence, the state of the art in the simulation of relativistic jets involves the computation of the emission, taking into account the appropriate relativistic and transfer of radiation processes, from the relativistic hydrodynamic results (Gómez et al. 1995, 1997; Mioduszewski, Hughes, & Duncan 1997; Komissarov & Falle 1997; Aloy et al. 2000, 2003; Agudo et al. 2001; and reviews Gómez 2001, 2002).

With these new numerical techniques it is now possible to study with great detail the generation, internal structure, and evolution of strong shock waves (Gómez et al. 1997; Mioduszewski, Hughes, & Duncan 1997; Komissarov & Falle 1997). Moving shocks, induced by introducing different type of perturbations at the jet inlet, provide a good explanation for the overall properties of superluminal components. In Gómez et al. (1997) simulations the propagation of a strong shock through a series of recollimation shocks is analyzed, showing that the latter may experience a temporary dragging of their position downstream, followed by upstream motions to recover their initial locations. These "wiggling" of quasi-stationary features do not correspond to actual fluid motions. On the contrary, they are related to phase motions, indicating the location of the recollimation shocks which may vary with changes in the jet hydrodynamic properties (i.e., jet Mach number). As shown in Gómez (2002), these phase motions can easily lead to wrong identification of components when the time sampling of the jet emission structure is not good enough. Furthermore, measured proper motions may actually depend on the angular resolution with which the jet is observed, since different convolving beams will be sensitive to different jet structures.

Agudo et al. (2001) simulations show that strong jet perturbations (which can be associated with bright superluminal components) interact with the underlying jet and external medium as they propagate. This excites pinch-mode jet-body instabilities, which in turn lead to the formation of recollimation shocks and rarefactions in the wake of the main perturbation. Figure 1 (*right*) plots the separation from the core as a function of time for these *trailing* components as computed by Agudo et al. (2001). They can be easily distinguished because they appear to be released from the primary superluminal component instead of being ejected from the core. The apparent velocities of the trailing features should range from subluminal closest to the core, to more superluminal near the leading component.

Figure 1 provides a one-to-one comparison between the actual inner motions of components in the radio galaxy 3C 120 and that of the simulations by Agudo et al. (2001), revealing a very good agreement. We can associate the new strong superluminal component (containing *o1* and *o2*; Fig. 1 *left*) with the leading perturbation (labeled *M* in the simulations; Fig. 1 *right*). Components *m1*, *m* and *m2* have been observed to emerge in the wake of the main superluminal component, and to present motions which are significantly smaller (1.2 $h_{65}^{-1}c$ for *m*). In addition, components *m1*, *m*, *m2*, *r* and *s* present increasing velocities with distance from the core, being the speeds of *r* and *s* the smallest (subluminal) detected in the jet of 3C 120.

Recent three-dimensional simulations have paid special attention to the response of relativistic jets to precession. Hardee et al. (2001) show that combination of the helical surface and first-body modes may lead to complex pressure and velocity structure inside the jet. They appear in synthetic emission images as differentially moving and stationary features in the jet, therefore providing an alternative mechanism for the production of jet components. In Hughes et al. (2002) the analysis of the jet emissivity for a precessing jet shows that this is in general a complex function of both, Doppler boosting and jet internal hydrodynamic conditions.

First three-dimensional relativistic hydrodynamic and emission simulations of a precessing jet through which a perturbation (shock wave) is set to propagate have been carried out by Aloy et al. (2003). Synthetic radio maps computed from the hydrodynamic model taking into account the appropriate light travel time delays are shown in Fig. 4. The introduced perturbation appears in the emission maps as a large region of enhanced emission. This stretching of the perturbation as seen in the observer's frame is produced by the light travel time delays between the front and back of the perturbation. As a consequence, the structure of the perturbation is magnified leading to brightness distribution variations within the component as seen in the observer's frame. This could have significant implications when interpreting the observations of superluminal sources. Identifying brightness peaks in radio maps with components may be misleading, as the component in this case may only be one of many brightness features caused by a single perturbation and may not be related to any physical structure on its own. Furthermore, a component may arise from different regions of the perturbation having different hydrodynamical properties, which could also change with time as the component evolves along the jet and interacts with the external medium and the underlying jet.

These simulations are therefore suggesting that shock-in-jet models may be an overly simplistic idealization when interpreting the emission patterns observed in actual jets. Indeed, most observable features should not be related to fluid bulk motions, but instead to a complex combination of bulk and phase motions, viewing angle selection effects, and non-linear interactions between perturbations and the external medium and/or underlying jet.

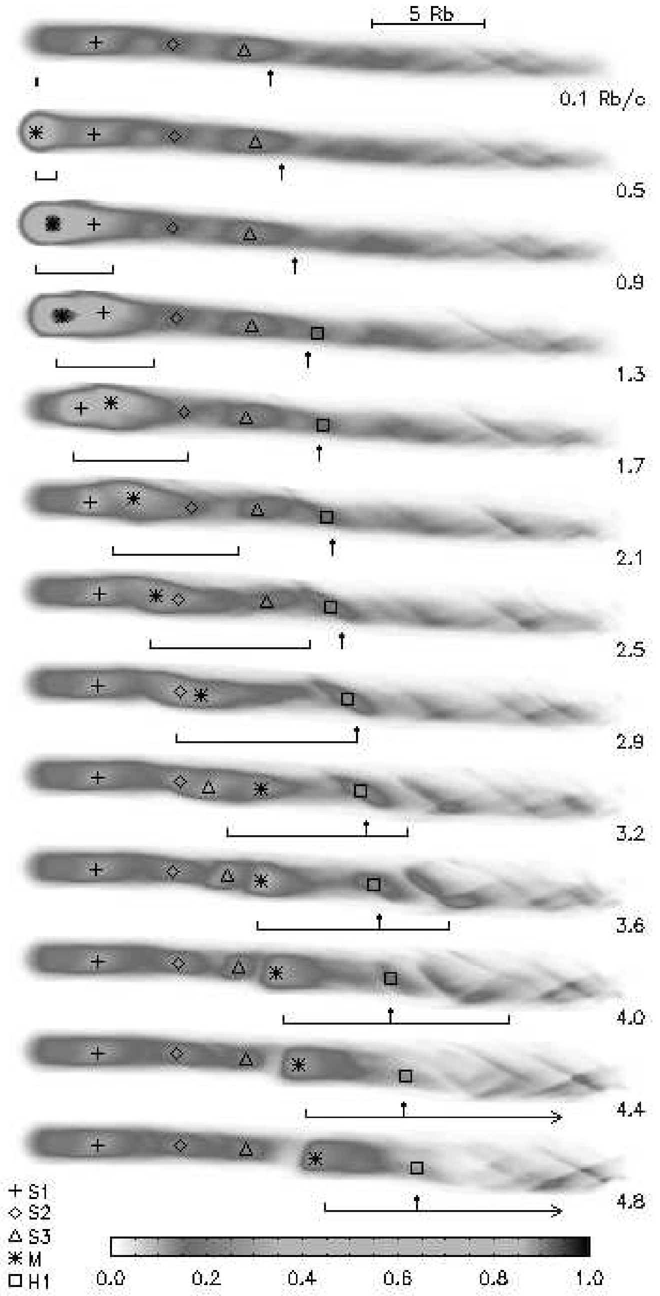

Fig. 4. Three-dimensional numerical simulation of a perturbation traveling along a precessing jet. Images show the time sequence (from top to bottom) of the computed radio emission (total intensity in arbitrary units) for a viewing angle of 15° and an optically thin frequency. Underbrackets indicate the extension of the imposed hydrodynamic perturbation. Knots in the emission are marked with different symbols. Reproduced from Aloy et al. (2003).

The improvement in the numerical modeling of relativistic jets will allow in the near future the computation of synthetic polarization emission maps making use of the recently developed relativistic magnetohydrodynamic simulations. These type of simulations would be capable of exploring the inner regions of jets in which the magnetic field could be dynamically important. Other efforts are aimed to the implementation of different equations of state, to account for the electron energy transport, and the computation of the synchrotron self Compton emission.

4. Conclusions

Intensive monitoring VLBI programs on multiple jets in AGN are providing information of the inner emission structure with unprecedented spatial and temporal resolutions. These are revealing the existence of intricate emission patterns, such as upstream motions or slow moving and quasi-stationary components trailing superluminal features. Numerical relativistic hydrodynamic and emission simulations are in good agreement with the observations, revealing the importance of such computations for the interpretation of actual sources. They also show that the non-linear hydrodynamic evolution of perturbations can determine the observed emission properties so that the interpretation of observed radio maps is error-prone when naively associating single shocks to superluminal components.

Both observations and simulations are suggesting that we are reaching a level of detail in which our radio images cannot just be idealized as a series of Gaussian moving components, each associated with a single shock wave. It is perhaps time to consider new ways to analyze our images, since otherwise we may overlook very important pieces of information present in our data.

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