A method to measure structural changes in GHz-Peaked Spectrum radio galaxies

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In order to overcome problems related to the estimation of uncertainties for separation measurements between source components of GHz-Peaked Spectrum radio galaxies, we have developed a method that compares two uv-data sets obtained at different epochs. This method parametrizes the most important structural change, the increase in separation between components, by rescaling the u and v axis of the amplitude interference pattern. It provides best-fit values for the parameters and uses a bootstrap method to estimate the errors in the parameters. From the u and v scaling factors the separation rate, hotspot advance speed and source age can be inferred. Here, we apply this method to GPS radio galaxy 2021+614.

1. Introduction

A crucial element in the study of the early evolutionary stages of extragalactic radio sources is to identify the young counterparts of old and extended double-lobed objects. Good candidates are GHz-Peaked Spectrum (GPS) sources because they are small in angular size as expected for young sources. They are characterized by a simple convex radio spectrum peaking at a frequency of about 1 GHz and are typically 100 pc in size. The best direct evidence for very low kinematic ages has now been found for a few GPS radio galaxies. Measurements of hotspot advance speeds, from which an age estimate can be made, have been obtained for 0108+388, 0710+439, 2352+495 (Owsianik *et al.* 1999 and references therein) and for 1943+456 (Polatidis *et al.* 1999). The hotspot advance speeds are typically of order $0.1\,h^{-1}\,c$, translating into ages of a few hundred to a few thousand years.

Here, we use one such object – the GPS radio galaxy 2021+614 at a redshift of 0.227 (Tschager *et al.* 2000) – to present the *Amplitude Interference Pattern method*; this method allows to calculate hotspot advance speed and kinematic age of the object and was developed to circumvent problems related to the estimation of uncertainties for separation measurements between source components.

2. Amplitude Interference Pattern Method

Our goal is to determine changes in source structure which occur between two epochs, directly in the uv plane using the amplitude interference patterns at each epoch. These changes are parametrized by a two-dimensional stretching factor whose components along the u and v-axis are $s_{\rm u}$ and $s_{\rm v}$, and by an amplitude correction factor $s_{\rm a}$. Our method provides estimates for these quantities and for their uncertainties. In this way, interpreting an observed shift in the position of the visibility amplitude minima between the two epochs as real expansion, we are able to determine source age, separation rate and hotspot advance speed.

2.1. *The two data sets used*

The VSOP (VLBI Space Observatory Programme) satellite HALCA observed 2021+614 at 5 GHz on November 6, 1997 together with a 15-station ground-based array composed of all 10 VLBA and 5 of the 10 EVN radio telescopes (Effelsberg, Medicina, Noto, Onsala and Torun) plus the VLA in phased-array mode. The on-source time was 9 hours for the ground telescopes and 6 hours for the satellite. The second data set at epoch 1982.9 was obtained by Conway and co-workers during a 9 hour global VLBI observing run using 4 antennas in the USA and the 100-m dish in Effelsberg (Conway *et al.* 1994). Compared to the 1997.8 data set, the 1982.9 coverage is sampled more sparsely and the two observations measure different spatial frequencies.

2.2. *Parametrizing the time evolution/structural change*

In order to obtain two data sets suitable for detecting an increase in separation between the two most prominent components we prepared the two uv data sets as follows: *1982.9* – a simple two-component model, comprising the two most prominent components from Conway's (Conway *et al.* 1994) six-component model for the 1982.9 observations, was Fourier-transformed back into the uv-plane. The model visibility amplitudes were calculated on a 561×561 pixel grid with mesh size of 0.5 Mλ ranging from -140.0 to 140.0 Mλ in both the u and v-dimension. This grid spacing was fine enough to detect a shift in the position of the first minimum of a few percent; *1997.8* – only baselines between ground-based telescopes were used. All the model components except the two most prominent, were uv-subtracted from the 1997.8 observations. In order to take account of the flux density variability of the components, the relative intensities of the two dominant components were adjusted to match Conway's values. Then, the visibility amplitudes for the 1997.8 data, sampled along the uv-tracks were gridded onto the 561×561 pixel mesh.

The gridding of the visibility data was done by assigning the visibility value to the nearest grid point. Multiple assignments near the uv-plane centre were averaged together, but no special weighting was applied to those data points. Fig. 1 shows a grey-scale plot of visibility amplitudes measured during the 1997.8 observation, prepared as explained above and gridded onto the 561×561 pixel mesh.

After having prepared the data sets we assumed that all remaining differences between the 1997.8 *data* and 1997.8 *model* are either due to real expansion or a residual multiplicative amplitude correction factor, $s_{\rm a}$. The parametrization of the change in separation was done by applying multiplicative factors, $s_{\rm u}$ and $s_{\rm v}$, to the sampled uv-points and associating the amplitude value of the original point with the new coordinates. Such an evolution model is, strictly speaking, correct only for unresolved source components which separate from or contract towards each other. For a pair of resolved components, modelled by elliptical gaussians, the resulting fringe pattern is convolved with an elliptical gaussian whose major and minor axis FWHM are inversely proportional to the corresponding parameters in the image plane. We investigated the impact of this simplification on the fitting process and concluded that it is minor and therefore negligible at the levels of accuracy involved.

2.3. *Fitting for the scale factors $s_{\rm u}$, $s_{\rm v}$ and $s_{\rm a}$*

The χ^2 parameter measuring the goodness of fit was defined as the sum of the squared differences of the visibility amplitudes:

$$\chi^2 = \sum_{i=1}^{N} \frac{[s_{\rm a}\, A_1(s_{\rm u}\, u_i, s_{\rm v} v_i) - A_2(u_i, v_i)]^2}{\sigma_i^2},$$

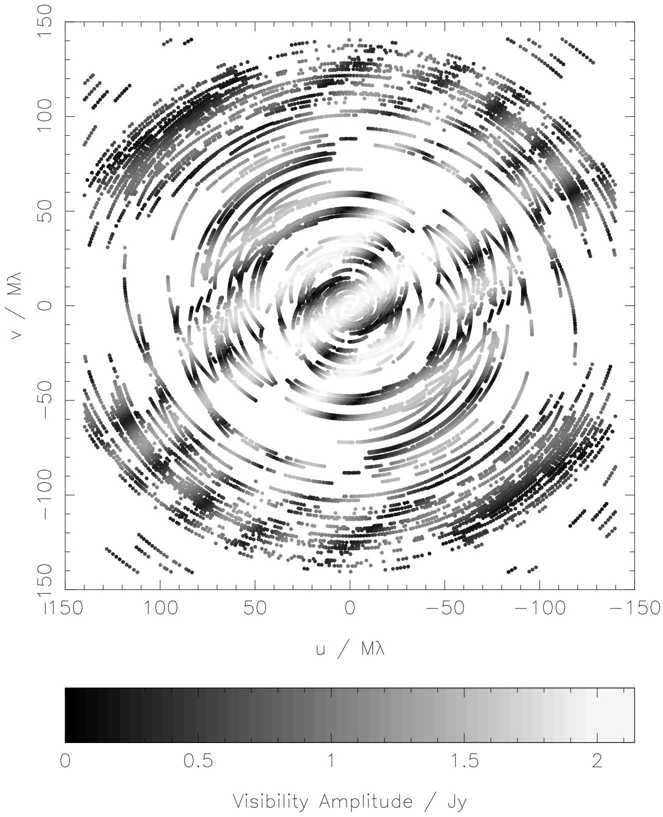

FIGURE 1. The uv-data sampled during the 1997.8 observing run gridded on the 561 × 561 pixel mesh and prepared for comparison with the 1982.9 *data*. The characteristic interference pattern shows alternating maxima and minima along the position angle defined by the two most prominent components.

where the indices 1 and 2 refer to the 1982.9 *model* and 1997.8 *data*, respectively; N is the total number of gridded visibility measurements; σ_i is the error associated with the visibility amplitude data point. Values > 1 for s_{u} and s_{v} indicate inward shifting amplitude minima, i.e. separating components as the source evolves. The result provided by the fitting routine gave a value of a few tens for the minimum reduced χ^2 rather than unity (for a good fit). This fit is too poor to use the (χ^2+1)-contour projections onto the parameter axes to determine the 1-σ uncertainties for s_a, s_{u} and s_{v}. Nevertheless, the procedure outlined above provided us the best-fit values for the overall amplitude correction factor, $s_{\mathrm{a}} = 0.88$ and for the scale factors in the u and v-directions, $s_{\mathrm{u}} = 1.0445$ and $s_{\mathrm{v}} = 1.0202$.

The percentage increase in separation s along the position angle defined by the u and v stretching factors s_u and s_v is given by

$$s = [(s_{\mathrm{u}}-1)^2 \sin^2 \psi_1 + (s_{\mathrm{v}}-1)^2 \cos^2 \psi_1]^{1/2}$$

and is 3.0%, where ψ_1 is the position angle defined by the two dominant components at epoch 1982.9.

The most difficult problem to tackle during the fitting process is to ensure that differences in component size and shape between different observations do not influence substantially the best-fit values of the parameters. The relatively high residual correction of 0.88 needed for the amplitude parameter, and the difference between s_{u} and s_{v}, are due to different component sizes at the two epochs. A more sophisticated method would take these details into account and be more widely applicable. However, for our purpose, which is limited to the determination of whether or not structural change in 2021+614 can be explained by subluminal motion of components, the systematic errors introduced are not relevant.

2.4. *Bootstrap method for estimating errors in the scale factors s_{u} and s_{v}.*

The bootstrap method is a very powerful error estimation technique applicable when there is not enough knowledge about the nature of the measurement errors to do a proper Monte Carlo simulation. We use this method to estimate the errors for the parameters s_{u} and s_{v}.

For the 1997.8 observation we generated one hundred uv-data samples each containing a different 50% of the original data. The visibility measurements in each sample were selected randomly. We fitted the one hundred data sets to Conway's model visibilities as outlined in the previous section for the whole data set, but this time fitting only the two scale factors s_{u} and s_{v}, and setting s_{a} to its best-fit value of 0.88. The standard deviations of the best-fit parameters provide the errors associated with these quantities. We found $s_{\mathrm{u}} = 1.0443 \pm 0.0005$ and $s_{\mathrm{v}} = 1.0212 \pm 0.0010$. This means that using 50% of the available data we are able to determine a 4% decrease in separation of the minima along the u-axis and a 2% decrease along the v-axis at an accuracy level of 5% and 10%, respectively – *clear evidence for real motion.*

3. Conclusions

The *Amplitude Interference Pattern method* is suitable for measuring an increase in separation of a few percent in radio sources with compact symmetric morphology. For instance, in the case of 2021+614 we measure a separation of $16.1\,h^{-1}$ pc at epoch 1997.8 and a separation rate of $0.12 \pm 0.01\,h^{-1}\,c$ between the two dominant components. These components are associated with lobes and/or hotspots. From separation and separation rate measurements we deduce an apparent age of 440 ± 35 yr. All results are measured in the source reference frame assuming $H_0 = 100\,h\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $q_0 = 0.5$.

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