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OQ208: a possible multi-wavelength polarimetric study with the SRT

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Abstract. We consider a possible contribution of the Sardinia Radio Telescope (SRT) to the polarimetric study of discrete sources. The foreseen capabilities are applied to the study of GHz-Peaked Spectrum (GPS) sources. The polarisation properties of these sources can be used to discriminate the absorption mechanism involved: Synchrotron Self Absorpion (SSA) would cause a change in the polarisation angle of 90° across the spectral peak, while Free-Free Absorption (FFA) would not. An accurate multi-wavelength polarimetric study could be carried out with the SRT and we apply the SRT specifications to a fake source with the radio spectrum identical to OQ208, and with a constant (unrealistic) fractional polarisation of 0.01. Considerations on the use of the SRT for a sky survey at 22 GHz are also given.

1. Introduction

GHz Peaked Spectrum (GPS) and Compact Steep Spectrum (CSS) radio sources are a substantial (nearly 20%) subclass of the AGN population, extensively studied in the last 20 years. The main characteristics of these objects are (O'Dea 1998): a convex radio spectrum peaking at ν_m < 500 MHz (CSS) or at 500 MHz < ν_m < 1 GHz (GPS); a compact size $l \leq 1$ kpc (GPS) or 1−20 kpc (CSS) with $\nu_m \propto l^{-0.65}$; a low degree of polarisation often associated with very high RM values (0−2000 rad/m^2); average spectral index of 0.56 ($\nu < \nu_m$) and −0.77($\nu > \nu_m$) with a lack of an observed ν_{break}; a wide range of redshifts (generally ≥ 0.2 with few exceptions), with higher values for GPS quasars; high radio power (Log $P_{1.4} \geq 25$ W Hz^{-1}); optical counterparts of GPS/CSS galaxies with interacting or disturbed morphology; strong high-excitation optical emission lines ([OIII]). Their global properties are compatible with those expected in very young objects, in particular the GPS sources (with estimated ages of ≈ 10^3 yr) are believed to be early-stage objects which are growing to become CSS objects (≈ 10^{4-5} yr), and then large-scale radio sources (≈ 10^{7-8}yr). This scenario is not completely defined and there are still a lot of conflicting opinions about the nature and the dynamics of these objects. Only recently the high-frequency part of the spectrum has been investigated and the data in the range 20−100 GHz are still poor.

One of the most controversal issues about the GPS regards the spectral shape and the mechanism causing the turnover. It is generally ascribed to Synchrotron Self Absorption (SSA), but some models based on Free Free Absorption (FFA, e.g. Kameno et al. 2000)

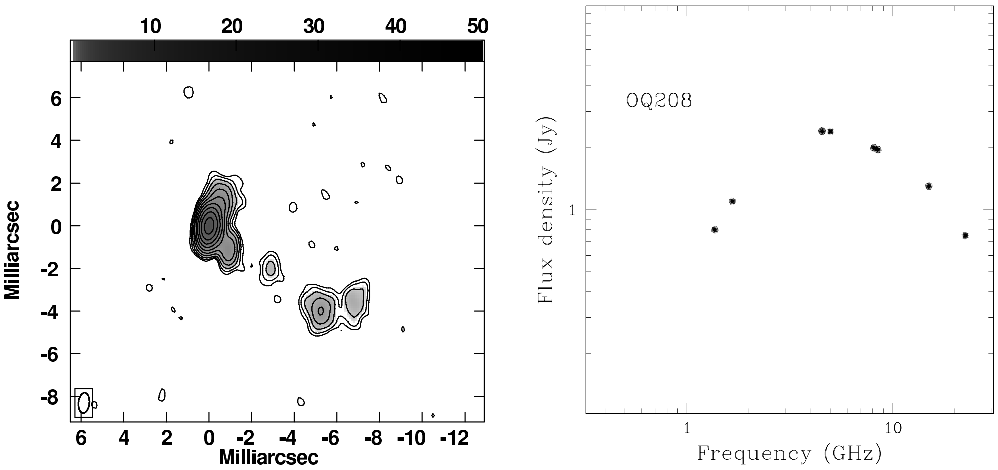

Fig. 1. *(left:)* VLBA 2-cm image of OQ208 taken in August 1997. The contour levels are 1, 2, 4, 8, 16, 32, 64, 128, 256, and 512 mJy/beam (from Lister et al. 2002); *(right:)* radio spectrum from simultaneous VLA observations (from Dallacasa et al. 2000).

were proposed as well. Today the presence of large amounts of dense ionised gas around the GPS/CSS is widely accepted but there is no clear evidence favouring one model over the other. Besides, it is also possible that both mechanisms play a role (Xie et al. 2005; O'Dea et al. 1991). Mutoh et al. (2002) proposed to use the polarisation properties of GPS/CSS to discriminate between the two absorption processes, as SSA would cause a change of 90° in the Electric Vector Position Angle (EVPA) in the transition from the optically thick to the optically thin regime. This argumentation clashes with the very low degree of polarisation usually detected in these sources and requires very accurate polarisation measurements at different wavelengths.

Here we discuss the role that the Sardinia Radio Telescope (SRT) could play in such a kind of study and simulate a typical polarimetric observation, outlining the basic technical features required to reach the goals.

1.1. OQ 208

OQ208 is one of the nearest (z = 0.0768) and best-studied GPS sources. The pc-scale structure seen in VLBI observations is characterised by two main regions separated by ≈ 7 mas (two microlobes or hot spots), quite asymmetric in flux density. At 15 GHz also a weak core is detected (Fig. 1, left panel). Because of its rather stable flux density, small angular size, OQ208 is often chosen as a calibration source. It is also known to be unpolarised ($< 0.5\%$) at cm-wavelengths. For our purposes, we consider a source with the same flux density as OQ208 but with a fractional polarisation of 1% at all frequencies (Table 1).

Table 1. Flux density and required sensitivity in Stokes U and Q, as a function of frequency

Frequency (GHz)	Flux Density (Jy)	5σ in U and Q (mJy)
1.37	0.809	5.72
1.67	1.105	7.81
4.64	2.403	16.99
5.00	2.398	16.96
8.09	1.988	14.06
8.43	1.940	13.72
14.97	1.292	9.14
22.30	0.719	5.08

2. The 90° jump in polarisation angle

Radio emission in AGNs is produced by synchrotron processes: a cloud of relativistic particles is injected into a small region in presence of a magnetic field. The simplest case of a homogeneous magnetic field and an isotropic velocity distribution of the relativistic particles can be considered as a first approximation. Usually it is assumed that the number density of electrons as a function of their energy is of the form:

$$N(E)\,dE = N_0 E^{-\delta} dE$$

where N_0 = constant, δ = constant.
Under these assumptions the emissivity (ϵ) and absorption (κ) coefficients are given by :

$$\epsilon(\nu) \propto N_0 B^{\frac{\delta+1}{2}} \nu^{\frac{-\delta+1}{2}}$$

$$\kappa(\nu) \propto N_0 B^{\frac{\delta+2}{2}} \nu^{\frac{-\delta-4}{2}}$$

where ν = frequency, B = magnetic field.

From the equation of radiative transport

$$I(\nu) = \frac{\epsilon(\nu)}{\kappa(\nu)}(1 - e^{-\tau})$$

where $I(\nu)$ = specific intensity, τ = optical depth:

$$\tau = \kappa(\nu) l_0$$

Where l_0 is the mean free path. We can distinguish two regions where

$$\tau \gg 1 \qquad \rightarrow I(\nu) \propto \frac{\epsilon(\nu)}{\kappa(\nu)}$$

$$\tau \ll 1 \qquad \rightarrow I(\nu) \propto \epsilon(\nu)\, l_0$$

In the optically thin region the polarisation vector is always perpendicular to the magnetic field vector. Le Roux (1961) studied the polarisation along the direction parallel (A) and perpendicular (B) to the magnetic field in the optically thick region and found the following:

$$\frac{\epsilon_B}{\epsilon_A} = \frac{3\delta + 5}{2} \qquad \frac{\kappa_B}{\kappa_A} = \frac{3\delta + 8}{2}$$

which implies that we have always:

$$\frac{\epsilon_A}{\kappa_A} > \frac{\epsilon_B}{\kappa_B} \qquad \rightarrow I_A > I_B$$

With the assumption that U=Q and V=0, we can express the degree of polarisation with the following:

$$P = \sqrt{2} \mid \frac{Q}{I} \mid = \sqrt{2} \mid \frac{I_B - I_A}{I_B + I_A} \mid$$

The position angle of the polarisation vector (EVPA) is parallel to the magnetic field if $I_A > I_B$ (optically thick regime) and perpendicular if $I_A < I_B$ (optically thin regime). Therefore a 90° change must occur across the peak at $\tau \approx 1$.

3. Technical requirements

As we usually deal with very low degrees of polarisation, a very high instrumental accuracy is required. It is expected that the SRT will offer an instrumental polarisation < 2%, along with a high stability in time. This value would be optimum for this kind of observation.

Furthermore, band depolarisation must be considered.

The rotation of the polarisation angle due to the Faraday effect is given by:

$$\chi = RM\lambda^2$$

where RM is the Rotation Measure.

This means that when we observe through a band of width $\Delta\lambda$ we measure an overall rotation of:

$$\Delta\chi = 2\,RM\,\lambda\,\Delta\lambda$$

Or, in terms of relative bandwidth:

$$\Delta\chi = 2\,RM\,\lambda^2 \frac{\Delta\lambda}{\lambda} = 2\,RM\,\lambda^2 \frac{\Delta\nu}{\nu}$$

A typical observation would require measurements at frequencies far from ν_m (both in the optically thin and thick regions) and a lot of observations around ν_m in adjacent bands in order to have a good sampling where the EVPA is expected to show the 90° jump.

In order to evaluate the effects of band depolarisation we can study the case of a source with $RM = 500$ rad/m^2 and determine the

Table 2. Summary of observational data of a potential polarimetric experiment on an OQ208 like source

Frequency (GHz)	Receiver Name	Sky Band (GHz)	Bandwidth (MHz)	SEFD (Jy)	Max $\Delta\nu_{allowed}$ (MHz)	σ_{rms} (mJy)	τ on source (sec)
1.5	L-2P	1.30−1.80	80	28.9	3.75	1.14	173
5.0	C-1B	4.30−5.80	1500	29.7	139	3.39	0.59
9.0	X-1G	7.50−10.40	2000	22.6	826	2.81	0.08
17	Ku-3G	14.40−19.80	2000	72.2	4250	1.83	0.78
22	K-4G	19.00−26.50	2000	124	11720	1.02	7.4

maximum bandwidth allowed by $\Delta\chi_{max}$ = 0.1 rad. Results are reported in Table 2.
To estimate the time needed for a measurement we need to consider the noise achieved by the SRT:

$$\sigma_{rms} = \frac{\sqrt{2}\,\alpha\, T_{sys}}{G\, \sqrt{\Delta\nu\, \tau\, n\, N_{IF}}} \quad \rightarrow \tau = (\frac{SEFD}{\sigma_{rms}})^2 \frac{1}{\Delta\nu}$$

where α (= $\frac{1}{\sqrt{2}}$) is a receiver constant, N_{IF} (= 1) the number of channels, n (= 1) the number of integrations, G the antenna gain, $SEFD = \frac{T_{sys}}{G}$ (System Equivalent Flux Density), and for a typical position switching observation:

$$\tau_{tot} = \tau_{on} + \tau_{off} + \tau_{sh}$$

τ_{on}= time on-source; τ_{off} (= τ_{on}) = time off-source; τ_{sh} = antenna total shifting time (~ 10 sec).

At low frequency (1.4 GHz) we estimated a confusion limit of 2.25 mJy/beam for the SRT using the source counts in Hopkins et al. (2003). An average polarisation of 10% for the confusing sources (which is overestimated!) would lead to a confusion limit of 0.225 mJy/beam in the polarimetric observation, quite below our requirements.

4. High-frequency surveys

The SRT could be used to investigate the existence of GPS sources peaking above 20 GHz. In case of SSA we can relate the turnover frequency to the angular size of the sources (more compact objects have higher ν_m; O'Dea 1998), and then those objects where the peak occurs at high frequency would be the youngest known so far (age ≈ 10^{1-2} yr).

4.1. Technical requirements

The SRT will be equipped with a 7-element multi-beam receiver working at 22 GHz. Considering the SEFD of the antenna at this frequency, a 2-GHz bandwidth, 2-channel integration, an FWHM of nearly 53″ per beam and a sampling factor of nearly 8, we can roughly estimate an observing time of 1 month to raster-scan a 500 deg^2 area to $\sigma_{rms} \approx 2$ mJy. A similar survey has been carried out at 15 GHz with the Ryle Telescope (9C survey; Waldram et al. 2003), which has covered a 520 deg^2 area to 25 mJy/beam. Their results suggest that with the SRT about 260 new High Frequency Peakers could be detected (tripling the number of already known sources!).

5. The SRT backend

One of the backend proposed for the SRT is a digital multi-function backend composed of 5 independent modules which can handle up to 40 IF inputs (100 MHz each) offering up to 10^6 channels. It would be possible to choose among various combinations of bandwidths and spectral resolutions. Such a versatile instrument could be used for polarimetry, spectroscopy and for pulsar studies.

5.1. Polarimetry

The maximum sampling and accuracy is needed around the spectral peak occurring at about 5 GHz for OQ208 (see Fig. 1, right panel). The receiver offers two 1500-MHz bands centered on the peak. The versatile backend of the SRT would receive two 1500-MHz IFs (one for each polarisation, downconverted to the 0.1−1.6-GHz range) that could be split e.g. into fifteen 100-MHz sub-bands. Each ordered couple of 100-MHz sub-bands would be then cross-correlated to obtain the polarisation measures, allowing a determination of the 90° EVPA jump in case it occurs.

5.2. A sky survey at 22 GHz

The search for High Frequency Peakers could be carried out with the 7-element 22-GHz array down to the confusion limit (50−70 μJy; Brand et al. 2005), in order to detect the highest number of objects. The SRT backend could then receive seven 4-GHz inputs in two polarisations for an estimated integration time of 18 minutes ($\sigma_{rms} \approx 60\ \mu Jy$) for each multibeam point map. Even if it is possible to use the digital backend to carry out this kind of observation, using 35 independent modules, it is worth evaluating the possibility to develop a total power backend which could more efficiently handle the huge amount of data collected from high-frequency sky surveys (≥ 22 GHz), which are characterized by long exposure times, small beam sizes (hence the need of multi-beam receivers) and large receiver bands.

6. Conclusions

We applied the specifications planned for the SRT to a study of GPS/CSS sources. As for the polarimetric study of known sources, we considered the position-switching technique and we obtained very short observation times. In addition, we expect very accurate values which would make the SRT an ideal instrument to carry out this kind of study. We recommend the use of a versatile backend which would provide a compromise between the small bandwidths necessary to avoid the band polarisation and the large bandwidths required to reach low rms noise values in a reasonable time.

As for the search for new High Frequency Peaked GPS sources, the use of multi-beam receivers is fundamental to carry out large, high-frequency surveys. At 22 GHz, the SRT will be equipped with a 7-beam receiver and we expect it to allow the detection of at least 180 new High Frequency Peaked sources. The presence of at least another multi-beam receiver at a higher frequency (e.g. 43 GHz) would be recommended. Besides, it could be worth studying the possibility to develop a continuum backend capable of easily managing the huge amount of data deriving from large high-frequency surveys.

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