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Radio-Variability in Radio-Quiet Quasars and Low-Luminosity AGN

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Abstract. We report on two surveys of radio-weak AGN to look for radio variability. We find significant variability with an RMS of 10-20% on a timescale of months in radio-quiet and radio-intermediate quasars. This exceeds the variability of radio cores in radio-loud quasars (excluding blazars), which vary only on a few percent level. The variability in radio-quiet quasars confirms that the radio emission in these sources is indeed related to the AGN. The most extremely variable source is the radio-intermediate quasar III Zw 2 which was recently found to contain a relativistic jet.

In addition we find large amplitude variabilities (up to 300% peak-to-peak) in a sample of nearby low-luminosity AGN, Liners and dwarf-Seyferts, on a timescale of 1.5 years. The variability could be related to the activity of nuclear jets responding to changing accretion rates. Simultaneous radio/optical/X-ray monitoring also for radio-weak AGN, and not just for blazars, is therefore a potentially powerful tool to study the link between jets and accretion flows.

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1. Introduction

In the past a lot of emphasis has been put on studying the radio variability of radio-loud AGN and specifically those of blazars (Wagner & Witzel 1995). There the radio emission is most certainly due to a relativistically beamed jet and one goal of multi-wavelength monitoring, including radio, is to understand particle acceleration processes in the jet plasma as well as the relativistic effects associated with the changing geometry and structure of jets.

On the other hand, for radio-weak AGN – here meant to include everything but radio-loud quasars – the situation is somewhat different and the database is much sparser. In fact, very few surveys exist that address the issue of radio variability in either radio-quiet quasars or low-luminosity AGN such as Liners and dwarf-Seyferts (e.g., Barvainis, Lonsdale, & Antonucci 1996; Ho et al. 1999). In many of these cases we are not even entirely sure that the radio emission is indeed related to the AGN itself.

It has been proposed that radio jets are a natural product of AGN, even that accretion flow and jet form a symbiotic system (Falcke & Biermann 1995), and this view seems to catch on (e.g., Livio 1997). This also implies a prediction for radio emission from nuclear jets across the astrophysical spectrum of AGN, including those being of low power or being radio-weak (Falcke & Biermann 1999). For radio-quiet quasars some evidence exists that this is indeed the case, like the finding of optical/radio correlations (e.g., Baum & Heckman 1989; Miller, Rawlings, & Saunders 1993; Falcke, Malkan, & Biermann 1995), or the detection of high-brightness temperature radio cores in a few radio-quiet quasars (Blundell & Beasley 1998).

Clearly, if (some of) the radio-emission in radio-weak AGN is coming from the central engine, we would expect to see a certain degree of radio variability as seen in other wavebands. Finding this would, firstly, confirm the AGN nature of the radio emission and, secondly, allow us to study the link between accretion flows and radio jet in more detail. In a symbiotic picture of accretion disk and radio jet one would expect to see a change in the accretion rate first reflected in a change in optical emission and then later in a change in the radio emission. The type of radio variability found in radio-weak AGN should also depend on whether or not the jets are relativistic and whether or not they are pointing towards the observer.

To start addressing some of these questions we have started a number of projects targeted at different classes of AGN – mainly radio-quiet quasars and LINERs. In the following we will present a report of first and preliminary results of these projects.

2. Radio-Quiet and Radio-Intermediate Quasars

To study the radio-variability of quasars we selected a sample of thirty sources from the PG quasar sample (Schmidt & Green 1983; Kellermann et al. 1994), the LBQS sample (Visnovsky et al. 1992; Hooper et al. 1995; Hooper et al. 1996), and the NVSS (Bischof & Becker 1997). The sources were selected to give a detectable flux density at 3.6 cm (8.5 GHz) above 0.3 mJy and to roughly equally fill the parameter space of the radio-to-optical flux ratio (R), including radio-quiet (RQQ, $R < 3$), radio-intermediate (RIQ, $3 < R < 100$), and radio-loud quasars (RLQ, $R > 100$, see Falcke, Sherwood, & Patnaik 1996). In the end we had 10, 13, and 7 objects respectively in each category.

The quasars were observed with the VLA roughly every month for eight epochs and then at one more epoch a year later. Integration times varied between 2 and 12 minutes. Where applicable, i.e. for some radio-loud quasars, we picked out the compact core and ignored emission from the extended lobes. The other sources appeared point-like on the maps.

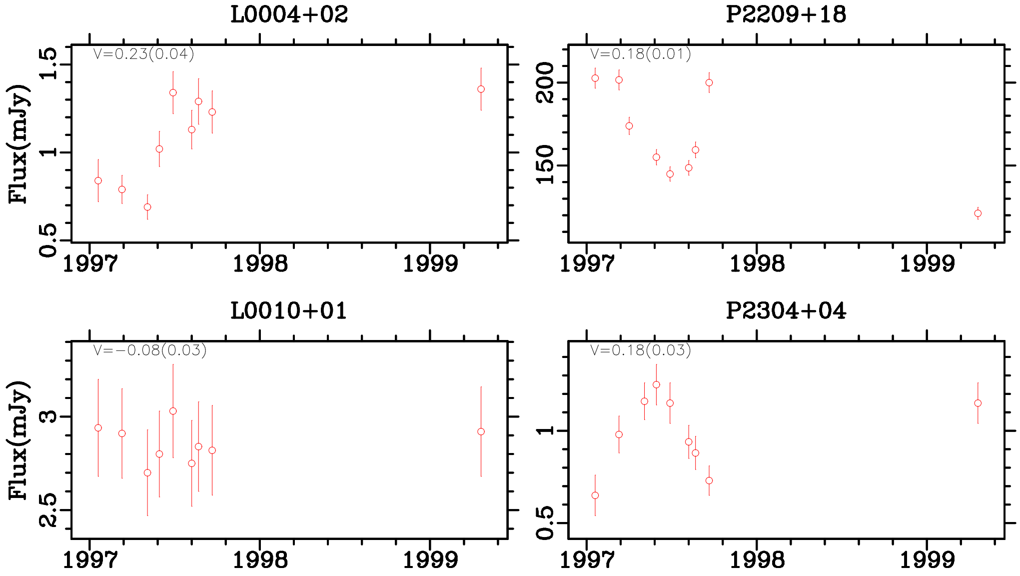

Figure 1. Light Curves of four selected quasars – three radio-quiet and one radio-intermediate – from our survey as observed with the VLA at 8.5 GHz over two years. Three of the sources show significant variation within a year, while L0010+01 does not.

A few sample light curves are shown in Figure 1. Error bars include statistical and systematic (calibration uncertainties) errors. The figure shows that in some cases we have distinct flux density variations within one year. Despite the rather low, i.e. milli-Jansky, flux density level we are able to clearly trace the variations from month to month in some of these galaxies. For comparison we also show one rather faint quasar where we consistently measure a constant flux density from epoch to epoch. This demonstrates that measuring radio-variability even in radio quiet quasars is not too much of a daunting task anymore.

The overall result of our survey is shown in Fig. 2, where we plot a debiased variability index V against the R-parameter. The index is defined here as

$$V = \frac{\sqrt{\Sigma\left(S_\nu(t) - \langle S_\nu\rangle\right)^2 - \Sigma\sigma^2}}{N \cdot \langle S_\nu\rangle}, \tag{1}$$

where N is the number of data points, σ is the measurement error, and $\langle S_\nu\rangle$ is the mean flux density (see Akritas & Bershady 1996). We set the index to

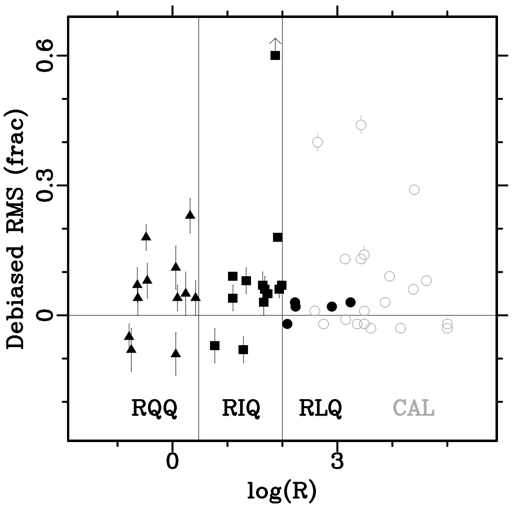

Figure 2. Debiased variability index for all sources in our survey versus the radio-to-optical flux ratio (R-parameter). A negative index indicates a non-significant variability. The sources are categorized simply as radio-quiet (triangles), radio-intermediate (boxes), and radio-loud (squares) according to their R-parameter alone. Open circles represent calibrator sources many of which are typically blazars. The variability index of III Zw 2 – the highest point in the diagram – is shown here only as a lower limit to keep the scale of the plot in reasonable bounds.

be negative when the value inside the square root becomes negative (i.e., for non-variable sources where the error bars are too conservative).

In about 80% of the sources we find at least some marginal evidence for variability. The variability index is about 10-20% in the RQQs and RIQs and only a few percent for RLQs. Most of the radio cores in the RIQs and RLQs have flat to inverted radio spectra and there may be a trend for higher variability with more inverted spectra.

We point out, that our sample does not include blazars. However, many of our phase calibrators naturally are. Surprisingly, these heterogeneously selected calibrators do show a variability that is not too distinct from the RLQs & RIQs in our sample.

The nature of RIQs had been discussed in the literature before. Miller, Rawlings, & Saunders (1993) and Falcke, Sherwood, & Patnaik (1996) had suggested that they could be the relativistically boosted counter-parts to radio-quiet quasars. And indeed three out of the two RIQs discussed by Falcke, Sherwood, & Patnaik (1996), III Zw 2 and PG2209+18, are included here and show some of the highest variability amplitudes observed in our survey. Recently Brunthaler et al. (2000) detected superluminal expansion – a clear indication of relativistic motion – in the former[1]. The fact that we find similarly strong variability in some RQQs could also point to the activity of relativistic jets. Clearly, since the radio emission at centimeter wavelengths should come from the parsec scale (because of self-absorption arguments, e.g., Falcke & Biermann 1995) – a variability timescale of months could not be achieved by jets with highly sub-luminal speeds.

Overall, the finding of variability in many RQQs and RIQs strengthens the conclusion that the radio emission detected in these quasars is indeed produced by the AGN. The rather low level of variability in the cores of radio-loud quasars is rather puzzling and might be related to larger black hole masses and thus longer timescales. The absence of relativistic beaming due to larger inclination angles (in contrast to blazars) and perhaps the presence of slow-moving cocoons surrounding the inner fast jets (e.g., Cygnus A, Krichbaum et al. 1998) could also play a role.

3. LLAGN: LINERs and Dwarf-Seyferts

Another group of AGN for which radio variability has not been studied in a coherent fashion are low-luminosity AGN (LLAGN). Almost a third of all galaxies in our cosmic neighborhood show evidence for low-level nuclear activity in emission lines, i.e. show Liner or Seyfert spectra (Ho, Filippenko, & Sargent 1997). In many of these cases it is not entirely clear whether the activity is due to stars or a central black hole.

We have used the VLA and VLBA to observe two samples of nearby LLAGN. One of them was a distance-limited sample of LLAGN within 19 Mpc, the other consisted of a collection of 48 well-studied Liners and a few dwarf-Seyferts. The VLA survey revealed a remarkable high detection rate of compact radio cores at 15 GHz (Nagar et al. 2000). Initial VLBA observations of the smaller sample confirm that these sources have high brightness temperature radio cores indicative of AGN (Falcke et al. 2000b). For the sources in our combined samples with flux densities above 3 mJy at 15 GHz and a flat radio spectrum we have now a 100% detection rate with VLBI (Falcke et al. 2000a). This shows that a large fraction ($\sim$50%) of LINERS and dwarf-Seyferts are indeed genuine AGN. In addition, having two frequencies and in some cases more, we find no evidence for highly inverted radio cores as predicted in the ADAF model: the (non-simultaneous) spectral indices are on average around $\alpha = 0.0$. In the six brightest sources we detect extended emission which appears to originate in jets. Together with the spectral indices this suggests that the nuclear emission at centimeter radio waves is largely dominated by emission from radio jets rather than an ADAF (Falcke & Biermann 1999), very similar to the situation in more luminous AGN. The energy released in these jets could be a significant fraction of the energy budget in the accretion flow. Hence, there is ample reason to also consider the radio variability of LLAGN and perhaps learn more about the underlying black hole/accretion flow system powering them.

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[1] However, boosting seems not to be the sole explanation for the enhanced radio flux in III Zw 2, strong interaction of the relativistic jet with the ISM or torus on the sub-parsec scale also seems to be important.

As a by-product of our observing program, we have a number of sources that were observed several times and hence can be used to obtain some initial and basic information on LLAGN radio variability. In fact, all 18 sources in our combined samples with flux densities above 3 mJy (the sample studied also by the VLBA) were observed at least two times; those who were part of our first sample (48 LLAGN) were observed three times, all epochs separated by roughly 1.5 years. All observations were made in a similar manner at 15 GHz with the VLA in A-configuration. This way we are not affected by resolution effects – from the VLBI observations we know that basically all the flux on this scale and at this frequency comes from a compact mas-component, i.e. the core.

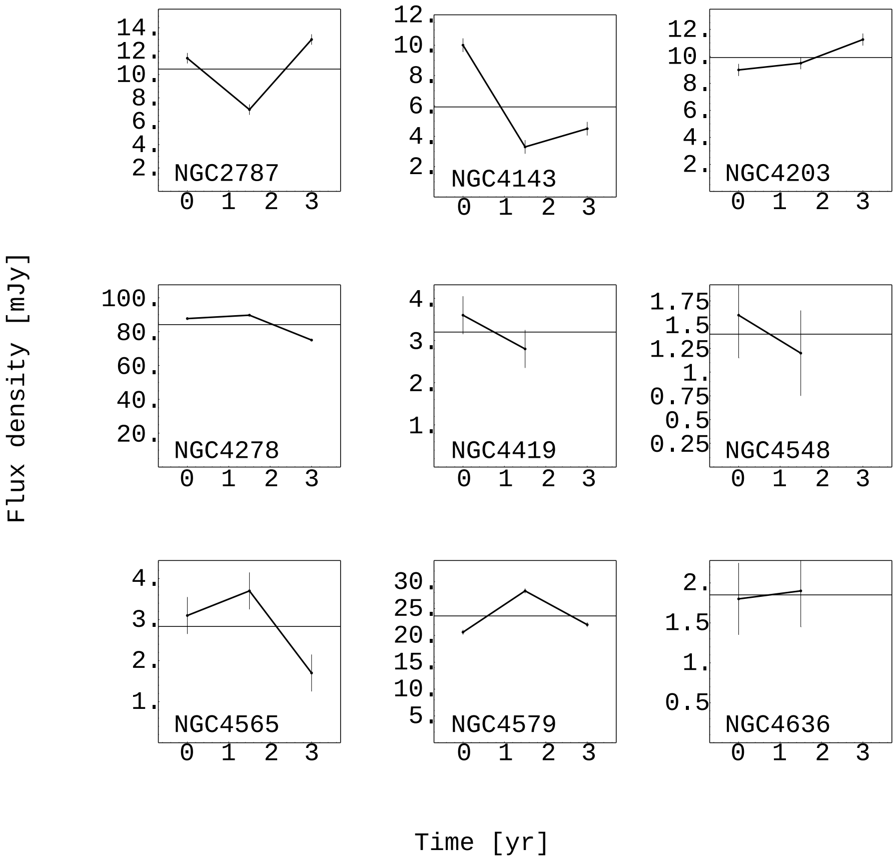

Figure 3. Radio light curves at 15 GHz taken with the VLA in A-configuration for radio cores in low-luminosity AGN from our sample. The vertical line gives the average flux density level for all epochs. The error bars only reflect the r.m.s. error and not calibration uncertainties.

As an example, simple light curves are shown in Figure 3. Again, the milli-Jansky level radio flux density is not a major problem in detecting variability. Surprisingly, we find a number of sources with rather large variations. Highly significant peak-to-peak variability of 200-300% is seen for example in the radio cores of NGC2787, NGC4143, and NGC4565.

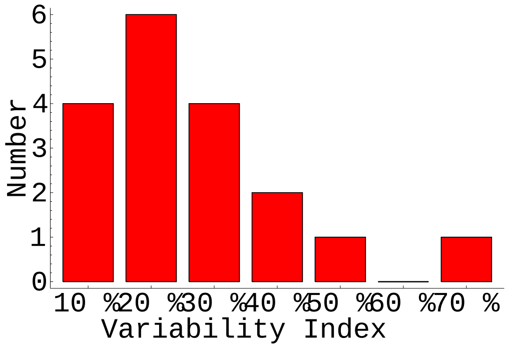

Figure 4. Distribution of variability index for all LLAGN in our samples with flux density larger than 3 mJy at 15 GHz. This is very preliminary, since it includes only 2-3 epochs per source.

For such sparsely sampled light curves a variability index is rather ill-defined for individual sources. Nevertheless, we can assume that in a statistically useful sample as ours the distribution of the variability index (i.e. the r.m.s. divided by the mean), as shown in Fig. 4, will have some meaning. The general trend of this distribution confirms the first impression from looking at the light curves: variability on a timescale of years is common place among LLAGN and amplitudes can reach rather large values – from 20-70%.

This variability is even larger than the one seen in quasars. The rather large fraction of LLAGN with radio cores and the fact that our sample was initially optically selected, speaks for a rather broad range of inclination angles. Strong variations in the accretion rate rather than effects of relativistic boosting therefore seem to be a more likely explanation for the variability. This would be in line with some of the X-ray variability seen in LLAGN where on scales of years the flux has changed by factors of a few (e.g., Uttley et al. 1999).

The apparent difference in variability index between LLAGN and RQQs seen here could be related to possibly smaller black hole masses in the former. Since we are probing only a narrow range of time scales in our programs it could well be that for larger black hole masses the time scale of strong variability is significant larger than a year and hence remains undetected. Alternatively, one could postulate a different type of accretion which is more volatile in LLAGN than in quasars. For example, if the accretion onto the central black hole is fed by stellar winds from a few sources only, as speculated for example for the Galactic Center (Coker & Melia 1997), then evolution and change in orbits of individual stars can have a much more pronounced effect on the overall accretion rate than in a situation where the accretion proceeds through a large scale and massive accretion disk.

4. Summary

We have established significant intra-year variability in a sample of radio-quiet and radio-intermediate quasars as well as in a sample of low-luminosity AGN. The variability in quasars strengthens the notion that also in supposedly radio-quiet quasars the radio emission is produced by the AGN – a large fraction of that very close to the central engine. The strong variability could be related to the presence of relativistic jets in at least some RQQs and RIQs.

In the radio cores of low-luminosity AGN the radio variability on the time-scales probed here – roughly one year – seems to be even higher. Lower black hole masses could be one possible explanation.

The detection of radio cores and radio-variability in these sources opens up the possibility to obtain a closer look on the connection between jet formation and accretion flows through coordinated optical/X-ray/radio monitoring also for radio-weak AGN. Changes in the accretion rate should be reflected also in the radio emission. Already now one can speculate that from the large radio-variability of some Liners and dwarf-Seyfert rather large fluctuations in the accretion rate are expected. Future long-term monitoring campaigns should therefore seriously consider including radio monitoring as well, even if the flux densities are only a few milli-Jansky in a compact core.

Acknowledgments. this works summarizes two partially unpublished results from various projects. The work was split in the following manner: RB & JL were involved in the quasar monitoring while AW & NN were involved in the LLAGN observations.

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