Astrophysical Phenomena Revealed by Space VLBI
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A Study of Young Radio-Loud AGN Using Space-VLBI

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Abstract

Gigahertz Peaked Spectrum (GPS) sources form a key element in the study of the onset and evolution of radio-loud AGN, since they are most likely the young counterparts of extended radio sources. Here we discuss space-VLBI observations of GPS sources, which enable us to obtain unprecedented angular resolution at frequencies near their spectral turnovers. Observed peak brightness temperatures of $10^{10.5-11}$ Kelvin indicate that synchrotron self absorption is responsible for their spectral turnovers. This is in close agreement with previous size – spectral turnover statistics for GPS sources. The combination of these new space-VLBI observations with ground-based VLBI observations taken at an earlier epoch, confirm the young ages for the most compact GPS galaxies of several hundred years.

1 Young Radio-Loud AGN

Although radio-loud Active Galactic Nuclei (AGN) have been studied for several decades, still not much is known about their birth and subsequent evolution. The recent identification of a class of very young radio sources can be considered as a major breakthrough in this respect, since it has opened many unique opportunities for radio source evolution studies.

Unfortunately, the nomenclature and use of acronyms in this field of research is rather confusing. This is mainly caused by the different ways in which young radio sources are selected. Selection of young sources is made in two ways, the first based on their broadband radio spectra,

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and the second based on their compact morphology. A convex shaped spectrum, peaking at about 1 GHz distinguishes young radio sources from other classes of compact radio sources. In this case they are called Gigahertz Peaked Spectrum (**GPS**) radio sources (e.g., O'Dea et al. 1991; O'Dea 1998). Similar objects, which are typically an order of magnitude larger in size, have their spectral turnovers shifted to the 10−100 MHz regime, causing them to be dominated at cm wavelengths by the optically thin parts of their spectra. These are called Compact Steep Spectrum (**CSS**) radio sources to distinguish them from the general population of extended steep spectrum sources (e.g., Fanti et al. 1990).

On the other hand, young radio sources are found in multi-frequency VLBI surveys, in which they can be recognised by compact jet/lobe-like structures on both sides of their central core. They are called Compact Symmetric Objects (**CSO**, Wilkinson et al. 1994). Their double sided structures clearly distinguish them from the large majority of compact sources showing one-sided core-jet morphologies. This implies that the luminosities of CSO are unlikely to be substantially enhanced by Doppler boosting. Larger versions of CSOs are subsequently called Medium Symmetric Objects (**MSO**) and Large Symmetric Objects (**LSO**).

The overlap between the classes of CSO and GPS galaxies is large and we believe that they can be considered to be identical objects. However, note that a substantial fraction of GPS sources are optically identified with high redshift quasars, which in general show core-jet structures (Stanghellini et al. 1997). The relationship between GPS quasars and GPS galaxies/CSO is not clear and under debate (Snellen et al. 1999). We therefore believe it is wise to restrict evolution studies to GPS galaxies and CSOs.

Evidence for Youth

Although it was always speculated that GPS sources were young objects, only recently has strong evidence been found to support this hypothesis. Monitoring several GPS sources over a decade or more using VLBI, allowed Owsianik & Conway (1998) and Owsianik, Conway & Polatidis (1998) to measure the hotspot advance speeds of several prototype GPS sources to be $\sim 0.1h^{-1}c$. These imply dynamical ages of typically 10^{2-3} years.

Additional proof for youth comes from analysis of the overall radio spectra of the somewhat larger CSS sources. Murgia et al. (1999) show that their spectra can be fitted with synchrotron aging models, implying ages of typically 10^{3-5} years.

The work of these authors shows that GPS/CSO sources are very young and most likely the progenitors of large, extended radio sources. This makes them key objects for radio source evolution studies.

Tools for Radio Source Evolution Studies

Several authors have used number count statistics and linear size distributions to constrain the luminosity evolution of radio sources (Fanti et al. 1995; Readhead et al. 1996; O'Dea & Baum 1997). All these studies find an excess of young objects in relation to the number of old, extended radio sources. This over-abundance of GPS and CSS sources has generally been explained by assuming that a radio source significantly decreases in luminosity over its lifetime. In this way, sources are more likely to contribute to flux density limited samples at young than at old age, causing the apparent excess.

However, in addition to their over-abundance, GPS galaxies are found to be significantly more biased towards high redshift than large extended radio galaxies (Snellen & Schilizzi 2000). This is puzzling since classes of sources representing similar objects at different stages of their evolution are expected to have similar birth functions and redshift distributions. Furthermore, it suggests that the interpretation of their number count statistics, which are averaged over a large redshift range, is not so straightforward. We have postulated a simple evolution scenario which can resolve these puzzles. We argue that the luminosity evolution of a radio-loud AGN during its first 10^5 years is qualitatively very different from that during the rest of its lifetime. This may be caused by a turnover in the density profile of the interstellar/intergalactic medium at the core-radius of the host galaxy, resulting in an increase in luminosity for young, and a decrease in luminosity for old radio-loud AGN with time. Such a luminosity evolution results in a flatter collective luminosity function for the young objects, causing their bias towards higher redshifts, and their over-abundance at bright flux density levels (Snellen et al. 2000).

An alternative explanation is that GPS sources are indeed young AGN, but mainly short-lived objects, which will never evolve into extended radio sources (Readhead et al. 1994). In that case, the two populations are not directly connected, and no similar cosmological evolution or redshift distribution is necessary.

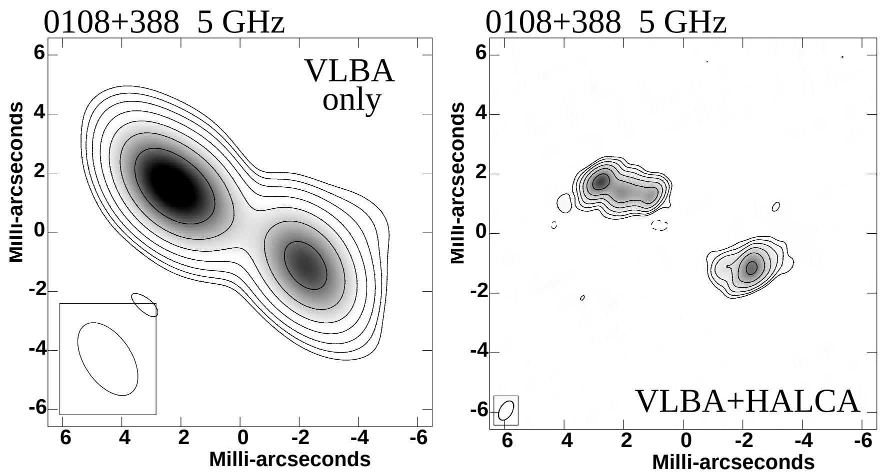
Table 1: Status of VSOP observations.

Name	id	z	Date of Obs 5 GHz	Date of Obs 1.6 GHz
0108+388	Gal	0.669	1999.08.06	1999.08.05
0248+430	QSO	1.316	1999.02.15	1999.08.18
0552+398	QSO	2.370	1999.03.23	1999.01.15
0615+820	QSO	0.710	1999.09.18	tbd
0646+600	QSO	0.460	1999.09.20	1999.09.27
1333+459	QSO	2.450	1998.06.22	1999.05.28
1404+286	Gal	0.077	1998.06.30	tbd
2021+614	Gal	0.227	1997.11.16	1999.09.28
1550+582	QSO	1.324	1998.07.02	–
1622+665	Gal	0.201	1998.05.24	–
0636+680	QSO	3.180	1999.09.19	–

2 Space-VLBI Observations of GPS Sources

In general, the angular resolution of VLBI observations at a certain observing frequency is limited by the size of the earth. The combination of ground VLBI stations with the Japanese satellite HALCA (part of the VLBI Space Observatory Programme VSOP), achieves a resolution typically 3 times higher than this ($\sim$ 1.5 mas and $\sim$ 0.5 mas at 1.6 and 5 GHz respectively). In particular, the study of GPS sources benefits from VSOP, since observing at a higher frequency to achieve a similar resolution is often not an option, because of their steep fall-off in flux density towards high frequency. Furthermore, their physical properties are most interesting around their spectral turnover, where differences in spectral indices within the source are more prominent than at high frequency.

We have been awarded VSOP observing time for 11 and 8 of the brightest and most compact GPS sources at 5.0 and 1.6 GHz respectively. Details and status of the observations are listed in Table 1. At the time of writing, all targets at 5 GHz, and 6 of the 8 sources at 1.6 GHz have been observed.



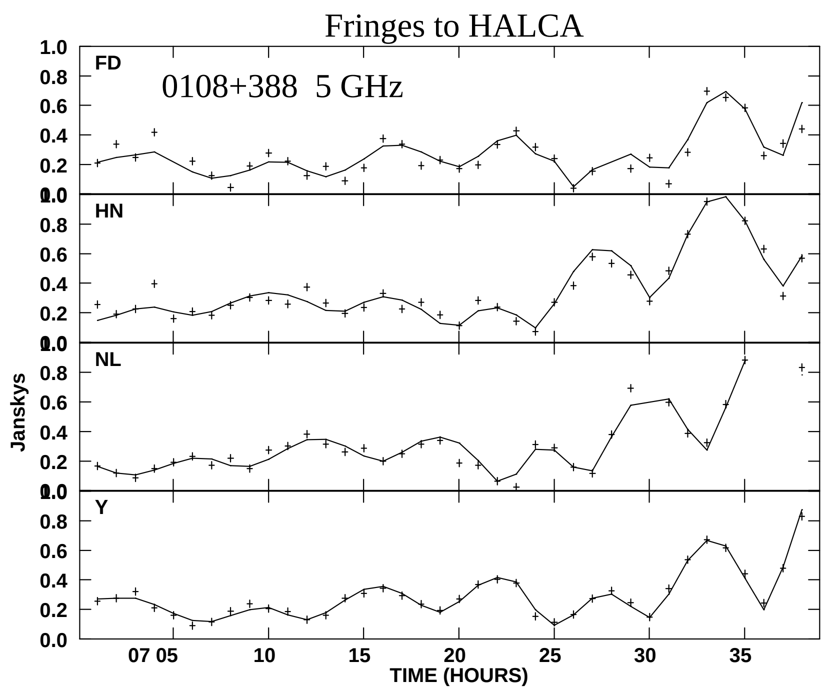


Figure 1: VSOP observations of 0108+388 at 5 GHz. The upper left panel shows the VLBA only image, the upper right panel shows the VLBA+HALCA image, and the lower panel shows some of the fringes of the VLBA antennas and the VLA to HALCA.

First Results and Discussion

A large fraction of the sources have now been imaged. Some examples are shown in Figures 1 and 2. Additional observations have been taken at 15 GHz with the VLBA to match the 5 GHz VSOP data in resolution, which will allow detailed spectral decompositions of the objects. In particular, this may sched new light on the nature of the GPS quasars and the role of Doppler boosting in these sources.

One of the first results of these observations are the high brightness temperatures observed of typically $10^{10.5-11}$ Kelvin. This indicates that these objects must be near their synchrotron self absorption (SSA) turnover at the observed frequency, making it very likely that indeed SSA is the cause of their spectral peaks. This is in agreement with the statistical arguments of Snellen et al. (2000), who found that among samples of GPS and CSS sources, the ratio of component size, as derived from the spectral peak assuming SSA, and overall angular size, are constant and very similar to those found for large extended radio sources. This not only implies self-similar evolution, but also provides strong evidence for SSA. Note however, that several authors argue that free-free absorption can not be ruled out for the smallest GPS galaxies (Kameno et al., these proceedings; Marr et al., these proceedings)

A valuable spin-off from these high angular resolution VSOP observations come from their comparison with ground-based VLBI images taken at an earlier epoch. Following the method of Owsianik & Conway (1998), we use these to derive dynamical ages for GPS sources. In this way, we find that the two dominant components at 5 GHz of 2021+614 (Fig. 2), have a larger separation at the epoch of the VSOP observations, compared to data from Conway et al. (1994) taken in 1982 and 1987. The increase in separation indicates a hotspot advance speed of ~ 0.1c, which implies an age of ~ 400 years for these components (Tschager et al. 2000). Preliminary analysis of 0108+388 (fig 1) shows an advance speed of 15 μas/yr, consistent with what is found by Owsianik, Conway & Polatidis (1998; 9 μas/yr). These observations confirm the young ages of a few hundred years for the most compact GPS galaxies.

3 Summary

GPS galaxies and CSO are now identified as classes of young radio sources. They form a key element in the investigation of the evolution of radio-loud AGN. We report on VSOP observations of 11 and

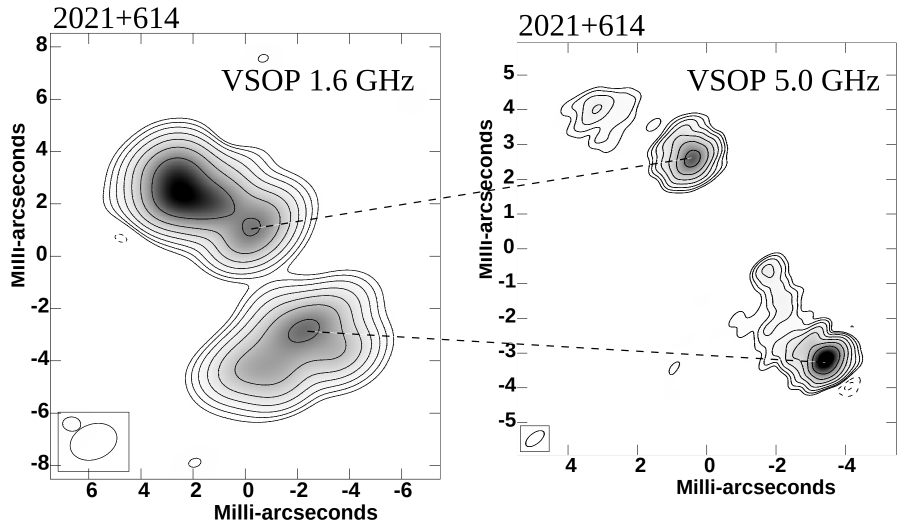


Figure 2: VSOP observations of 2021+614 at 1.6 and 5 GHz. The dotted lines connect the two dominant features at 5 GHz with their position at 1.6 GHz. Note the importance of sufficient resolution near the spectral turnover frequency, where the differences in spectral index between the components are most prominent.

8 bright GPS sources at 5.0 and 1.6 GHz frequency respectively. First analysis indicates high brightness temperatures consistent with synchrotron self absorption as the cause of their spectral turnover. Comparison with ground-based VLBI datasets taken at earlier epochs confirm the very young ages for the most compact GPS galaxies of a few hundred years.

Acknowledgements. We gratefully acknowledge the VSOP Project, which is led by the Japanese Institute of Space and Astronautical Science in cooperation with many organizations and radio telescopes around the world.

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Corrections to VSOP Symposium Proceedings
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* In the contents, the author list for the paper starting on page 79
  is incomplete and should read
  "Ignas Snellen, Wolfgang Tschager, Richard Schilizzi et al."

* In the preface, "Orian-KL" should be "Orion-KL"!!!

* The caption to Color Figure 3 refers to the source 1928+734,
  which should be 1928+738.

* In the summary section on page 49 (Murphy et al.), the sentence
  "In that time, we have observed a variety of
   structural changes in the inner jet region near the region."
  should read
  "In that time, we have observed a variety of
   structural changes in the inner jet region near the core."

* In the references on page 175 (Fomalont et al.) and page 182
  (Moellenbrock et al.) "Fomalont et al. 2000" should be updated to
  "Fomalont, E.B., Frey, S., Paragi, Z., Gurvits, L.I., Scott, W.K.,
  Edwards, P.G., Hirabayashi, H., 2000, ApJS, 131, 95"

* On page 217 (Lovell et al), the fourth line of the final paragrpah of
  section 1 should say "(see figure on page xviii)"

* In the references on page 233 (Sambruna) an extraneous "439"
  was introduced during the editing process into the reference
  for Catanese 1999.

* In the First Author List on page 327 (in the Index), the following
  line is missing
  Junor, W.   13