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Compact Structures in Flat-Spectrum Extragalactic Radio Sources

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Abstract. We have used visibility data obtained with the VLBA at 15 GHz to examine the most compact structures in 160 flat-spectrum extragalactic radio sources. With projected baselines out to 440 million wavelengths we are able to study source structure on angular scales as small as 0.12 mas. For about 40% of the sources, at least at one epoch, more than half of the flux density is unresolved on the longest baselines. These objects may have dimensions less than 0.12 mas. The most variable sources tend to have the most compact structure. Typical lower limits to the brightness temperature are in the range of 10^{11} to 10^{12} K but extend up to 10^{13} K; this being an apparent excess of the inverse Compton limit for stationary synchrotron sources. Longer baselines, such as shall be available in future space VLBI missions, are needed to study the most compact high brightness temperature regions in these sources. The fringe visibilities of the γ-ray loud AGN show, on average, higher values than for γ-ray quiet AGN and they are more variable. This supports a concept of a common emission mechanism at radio and γ-ray wavelengths. A visible correlation of VLBI–filled aperture monitoring data is also discussed.

1. Introduction

The structure and physics of the regions nearest to a super massive black hole where relativistic particles are accelerated can be studied with a linear resolution of a parsec or less by VLBI. The highest resolutions are achieved by earth to space interferometry. The first space VLBI missions (Levy et al. 1989, Hirabayashi et al. 1998) have already increased the baselines by a factor of about 3 in comparison with the maximum baselines of ground-based interferometers. By extending the baselines by a factor of ≥ 10 in expected space VLBI missions it will be possible to study very compact structures with high brightness temperature. E.g., for the planned *RadioAstron* mission the fringe size approaches the angular size of the gravitational radius of nearby super massive black holes such as in M 87. Such very compact regions with high surface brightness are surely present in pulsars and perhaps in the rapidly variable Galactic and extragalactic radio sources, as indicated by their time variability.

In this paper we analyze 15 GHz VLBA observations of 160 flat-spectrum compact extragalactic sources (sample selection procedure and first epoch maps are published by Kellermann et al. 1998; Zensus et al. 2002). These data are comparable with the space VLBI data from VSOP (Hirabayashi et al. 1998) obtained on longer baselines but at longer wavelengths and with lower accuracy. We use the data to study most compact structures and the way they change with time.

2. Observational Data in Use

In this analysis we have used visibility monitoring data obtained up to 1998. Three epochs of 15 GHz VLBA observations were available for each source, on average. For every source we have calculated the total flux density $S_{\rm tot}$ within a map and the flux density from the most compact component $S_{\rm comp}$. The "compact" flux density is defined by the data obtained at baseline projections near 400 Mλ. VLBA core parameters were derived for each source using DIFMAP.

A small subset of our sources are only slightly resolved even at the longest spacings. With the robust self calibration of the VLBA, we are able to state with some confidence when a source or component of a source has a fringe visibility greater than 0.9 at the longest spacings of about 400 million wavelengths, corresponding to an angular dimensions less than 0.12 mas.

We have also considered the total flux density $S_{\rm fa}$ at 15 GHz determined from observations with filled-aperture antennas. Data from the UMRAO and RATAN–600 monitoring programs (Aller et al. 1985; Kovalev et al. 1999) were used.

3. Discussion of General Characteristics

Figures 1 and 2 present the distributions of the flux densities and flux density ratios (or "indices of compactness"). We see that many sources have considerable correlated flux density at projected baselines more than 400 Mλ. More than a third of the sources have $S_{\rm comp}/S_{\rm tot} > 0.5$ and 90% of the sources have the unresolved flux density greater than 0.1 Jy. For 70 of these sources the flux density of the most compact component is greater than 0.5 Jy.

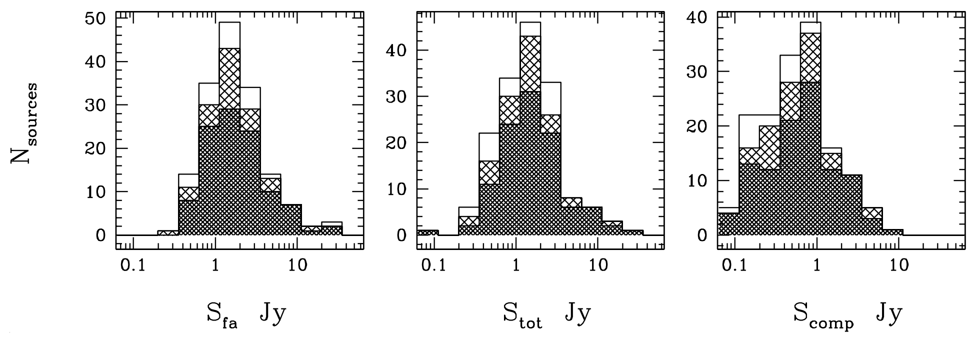

Figure 1. Distributions of flux densities $S_{\rm fa}$, $S_{\rm tot}$, $S_{\rm comp}$. We separate here and in Figure 2 quasars (most hatched area) from BL Lacs (medium hatched) and radio galaxies (empty).

The good correlation between $S_{\rm tot}$ and $S_{\rm fa}$ indicates that for most sources the VLBA sees nearly all of the flux density, and that there are no significant systematic errors in the flux density scale of the VLBA. Aside from the few sources that clearly have large scale structure, the mean compactness index $< S_{\rm tot}/S_{\rm fa} >$ for the sample is about 0.86. Several objects have a compactness index $S_{\rm tot}/S_{\rm fa} > 1$; most likely, this is due to the source variability and the non-simultaneity of the VLBA and filled aperture observations. Sources with the compactness index $S_{\rm tot}/S_{\rm fa}$ close to 1 at all epochs are suitable for calibration of other VLBI observations.

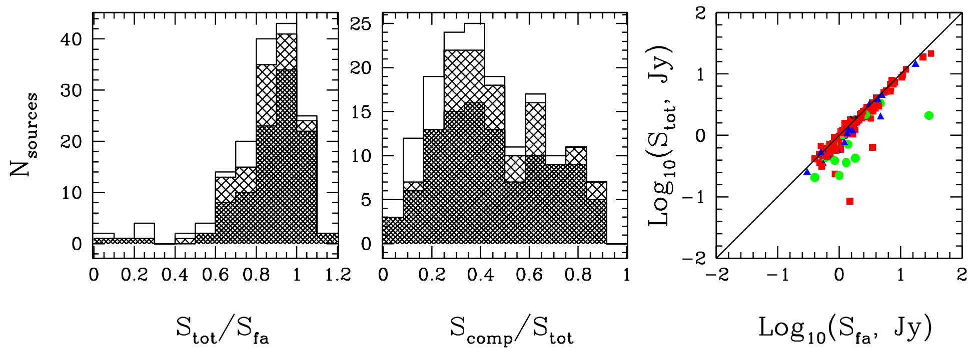

Figure 2. Source distributions on indexes of compactness $S_{\rm tot}/S_{\rm fa}$, $S_{\rm comp}/S_{\rm tot}$ and $S_{\rm tot}$–$S_{\rm fa}$ dependence (quasars are labeled by squares, BL Lacs—by triangles, radio galaxies—circles).

Generally, there are no major distinctions among sources included in Figures 1 and 2, although the radio galaxies have on average a smaller compactness index. This is easily interpreted in the context of the unified scheme (see, e.g., Urry & Padovani 1995). The radio galaxies probably have a greater angle between a jet and a line of view than quasars and BL Lacs do and have smaller beaming factor; thus, the radio galaxies are viewed as more extended and more symmetric objects.

The peak of the $S_{\rm fa}$ distribution corresponds to the selection limit of the sample. The peak position and the shape of the left wing reflect the discrepancy between the actual 15 GHz flux density and the value estimated from extrapolation by Kellermann et al. (1998) and Zensus et al. (2002), largely due to the variability of the sources.

The brightness temperature distribution of VLBA cores has a maximum near $3 \cdot 10^{11}$ K and extends up to 10^{13} K, which is close to the limit attainable by the VLBA for a source of a few Jansky. In many cases the measurement refers only to the upper limit of the angular sizes, corresponding to our limiting angular size of about 0.12 mas, defined by the beam size and the signal-to-noise ratio. Thus, the real brightness temperatures may extend to the higher values, beyond the synchro-Compton limit of 10^{12} K (Kellermann & Pauliny-Toth 1969). Such excessive brightness temperatures might be due to the Doppler boosting, transient events, coherent emission, emission by relativistic protons (see, e.g., Kardashev 2000, Kellermann 2002).

About one third of all VLBI cores involved are unresolved along one direction having a dimension less than 0.12 mas. For the nearest object, M 87, this corresponds to a linear size of $3 \cdot 10^{16}$ cm. Galaxies typically have larger VLBI cores. As many sources appear to have unresolved structures, we have examined a one dimensional brightness distribution along and perpendicular to the jet axis for each source. The CLEAN component model has been convolved with a knife-like beam (HPBW: 0.12×20 mas) which is very narrow along the direction of the scan and is very wide in the perpendicular direction. For many sources the fan beam distribution includes a considerable number of unresolved structures (often representing an unresolved width of a jet). If a direction of a jet is known, a (u, v)-coverage could be planned most effectively for a task of resolving a jet width. This task is attractive for planned space VLBI missions with stretched orbits (e.g., *RadioAstron*). In the modeling of annual changes of the timescale of scintillation variability (see, e.g., Jauncey & Macquart 2001; Rickett et al. 2001) it is also important to take into account an orientation to the Earth orbit of a VLBI core with unresolved width.

For the sources with many epochs of observations, VLBI core parameters (in particular, the brightness temperature) vary significantly with time. For 20% of the objects, the flux density of a core varies by a factor of two or more. The most variable sources tend to have the most compact structure.

On modeling the broad band radio spectra of compact extragalactic radio sources (Kovalev et al. 2001), we derived that a compact relativistic jet must be responsible for the centimeter and millimeter part of the spectrum. It is also supported by the compactness analysis done in the present paper (see Fig. 2). Consequently, correlation of a long term variability between $S_{\rm tot}$ and $S_{\rm fa}$ was anticipated. A check on its presence gave us a positive answer.

4. Radio Sources Detected by EGRET

The third catalog of high energy γ-ray sources detected by the EGRET telescope of the *CGRO* (Hartman et al. 1999) includes 66 high-confidence identifications of blazars. While the γ-ray sources were identified with flat-spectrum radio loud extragalactic radio objects ($\alpha > -0.5$, $F \sim \nu^{\alpha}$), not all radio sources with such characteristics have been detected as γ-ray sources. However, we note that the range of flux density detected by EGRET is very limited, so that the number of γ-ray detections may rise considerably with improved sensitivity, in contrast to the distribution of radio flux density where there are well defined radio loud and radio quiet objects.

Kellermann et al. (1998) did not find any clear differences in the milliarcsecond structure between the EGRET subsample (20% of radio sample) and the rest of the sources. We find no significant difference in the compactness parameter $S_{\rm comp}/S_{\rm tot}$ between EGRET detections and the sources of undefined γ-ray status (see Fig. 3, left). However, the EGRET non detected sources (von Montigny et al. 1995) show remarkably lower compactness at mas scale than the EGRET detections do. The situation changes if we use only the maximum values of the compactness index for each source (Fig. 3, right). For the EGRET detected sources the peak of the distribution becomes more pronounced: maximum compactness indexes of more than 75% of the EGRET detections are greater than 0.5. The distributions for all other sources become flatter. Notice also that two γ-bright objects with the lowest compactness were observed only once, and an object with the maximum compactness index 0.2 is the well known quasar 3C 273 with large resolved jet. Probably, sources are γ-ray strong only during the initial stages of strong radio flares (as it was proposed by Valtaoja & Teräsranta 1996) when the radio flux density is generally emitted by compact unresolved components. It is not clear if the relation between the observed γ-ray emission and radio compactness is the result of inverse Compton scattering mechanism, or the γ-ray emission is the synchrotron radiation of electrons in

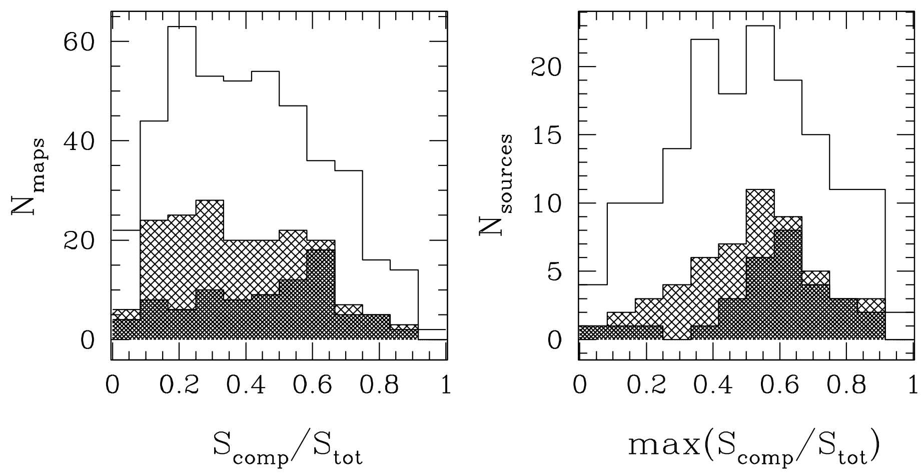

Figure 3. Distributions over the compactness index $S_{\rm comp}/S_{\rm tot}$: left—for all the maps analyzed; right—for all the sources (for each source a map with the maximum value of $S_{\rm comp}/S_{\rm tot}$ is chosen from the multi-epoch data). We separate flat-spectrum radio sources detected by EGRET with high confidence (most hatched area) from EGRET not detected sources (medium hatched) and the objects of undefined γ-ray status (empty).

the high energy tail of distribution of the electrons which are responsible for the radio radiation. With the next generation of γ-ray telescopes, such as *GLAST*, the sensitivity may be sufficient to actually separate the class of γ-ray loud and γ-ray quiet objects and better define the relation between radio and γ-ray emission of the sources.

5. Conclusion

We have carried out an analysis of the observational data of 160 extragalactic objects, obtained with the VLBA at 2 cm as a part of a program to monitor the structure of strong quasars and AGN (Kellermann et al. 1998, Zensus et al. 2002). We find that there are many sources with significant compact structure on sub-milliarcsecond scales. About 90% of the objects from the sample have unresolved flux density greater than 0.1 Jy. For 40% of the objects in the sample, more than half of the flux density comes from unresolved features. We have compiled a list of 70 sources with an unresolved structure stronger than 0.5 Jy. These sources will be good candidates for a study with space VLBI. A small subset of the sources are only slightly resolved even at the longest spacings and have angular size less than about 0.12 mas. About one third of all VLBI cores are unresolved along one direction with a corresponding dimension less than 0.12 mas. For the nearest object, M 87, this implies a linear size of $3 \cdot 10^{16}$ cm.

The distribution of brightness temperatures of the cores peaks at $3 \cdot 10^{11}$ K and extends up to 10^{13} K. For many sources the value of the brightness temperature is only a lower limit. Brightness temperatures in excess of the inverse Compton limit of 10^{12} K can be explained as the result of the Doppler boosting, transient phenomena, coherent emission, or synchrotron emission by relativistic protons.

EGRET detected radio sources show, on average, higher values of fringe visibility and more variability of their most compact structure than non EGRET sources, supporting models which relate the radio and γ-ray emission, such as inverse Compton scattering or synchrotron emission from a common electron energy distribution.

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