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Intraday Variability of Flat-Spectrum Radio Sources

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Abstract. The characteristics of rapid variability of flat-spectrum radio sources are reviewed. A large fraction of the blazar population is found to show variability on timescales shorter than one day throughout the entire electromagnetic spectrum. The spectral indices and polarization characteristics change equally fast.

Structure functions of the well-monitored sources show pronounced breaks on scales of about 10 to 50 hours, with flatter slopes towards the fast end. This illustrates that Intraday Variability (IDV), i. e. the high frequency end of the power spectrum is qualitatively different and requires different mechanisms than slower variations.

While intrinsic IDV provides direct clues on small-scale structure over fifteen decades in frequency, extrinsic contributions from interstellar scattering contributes at the lowest frequencies, and remains difficult to disentangle from the intrinsic effects.

1. Variability—Or: What is the Smallest Relevant Scale in an AGN?

The flux density received from quasars is known to be variable essentially since quasars were identified as such. The fact that quasars—showing high redshifts implying huge distances and large intrinsic luminosities—varied on short timescales led to the recognition as compact objects and was a prime motivation for aiming for high angular resolution. Since these early days many studies attempted to derive the characteristics of these variations. Important monitoring studies were initiated decades ago, and fortunately several of them are still going on (such as, e. g., the Michigan studies at cm wavelengths, the Metsahovi monitoring in the mm regime (see Aller, Aller, & Hughes and Valtaoja, these Proceedings, page 107 and page 35) and the Rosemary Hill program in the optical wavelength regime, and many others). These investigations established the variability properties in the regime from weeks to decades (roughly three orders of magnitude). In spite of a few early reports of faster variations, this regime was less well explored until the nineties. Following up on investigations of flickering in the radio domain the improved sensitivities in many wavebands (and the exploration of entirely new regimes, such as the gamma-ray band) triggered many studies of fast variability. It was recognized that the variability amplitude of IDV exceeds the extrapolation of the power spectra derived from longer-term variability. This excess can be identified as a break in the structure function of these sources on scales of a about one day with a slope which is getting flatter towards shorter timescales. The break and its position gave rise to the term Intraday Variability. The status of IDV (variability as fast as about 50 h or less in the observers frame) up to 1994 was reviewed by Wagner & Witzel (1995, hereafter WW95). The field has since become ever more interesting and this paper attempts to review some of the recent progress.

The main interest in studying fast variations arises from the desire to identify the smallest relevant length scale. Causality arguments link the observed timescales dt to the largest possible dimension of the emitting region $D < c\, dt/(z+1)\, \mathcal{D}$ with the velocity of light c and relativistic Doppler factor $\mathcal{D}$. Typical dt observed in many flat-spectrum radio sources are of the order of days and even a slow IDV source, with a characteristic timescale of 50 h, lying at a

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cosmological distance of z=1 has an angular diameter of $\phi = \mathcal{D}\ 10^{-4}$ mas which is orders of magnitude smaller than the most compact structure which can be resolved with mm-VLBI or space-VLBI (see, e.g., Krichbaum et al. and Ulvestad & Linfield, these Proceedings, page 37 and page 397) for any plausible Doppler factor $\mathcal{D}$. IDV hence provides important constraints on the sizes of sub-volumes which produce an appreciable fraction of the total flux. Another way to express the enormous compactness of IDV sources is the brightness temperature. In the most extreme cases the derived brightness temperatures exceed 10^{18} K, more than 6 orders of magnitude in excess of the limit set by catastrophic Compton cooling (10^{12} K). Most of the suggestions put forward to resolve this discrepancy predict the existence of large amounts of highly relativistic particles. With the benefit of hindsight it is hence not surprising that most Intraday Variables turned out to be amongst the most luminous sources in the gamma-ray range (and vice versa). As will be shown below, not only the average spectral energy distribution span the entire accessible wavelength range. The flux densities change on similar timescales over more than 15 decades in energy and seem to be closely correlated in a number of cases.

2. Intraday Variability Throughout the Electromagnetic Spectrum

2.1. IDV at Radio Frequencies

The early studies for radio-IDV (Heeschen et al. 1987; Witzel et al. 1986) established variations on timescales of about a day. Subsequent, more detailed investigations with denser sampling on individual sources established more rapid variability (a few hours, Quirrenbach et al. 1989). Systematic investigations found many of the IDV sources to vary with low amplitudes during several tens of minutes (Kraus et al. 1996, e.g., Figure 1). The small amplitudes require high accuracies. Comparably fast variations have also been found in the spectral indices and polarization properties (Kraus et al. 1996 and these Proceedings, page 277). Significantly larger amplitudes of variability on these timescales have been found by Kedziora-Chudczer et al., these Proceedings, page 271. As pointed out by Walker, these Proceedings, page 285, the frequency dependence measured in some of their sources suggests a significant influence from interstellar scintillation (ISS) on the flux variability. Gabuzda and co-workers (these Proceedings, page 265, page 273) found indications for changes of polarization characteristics in VLBI maps during a few hours.

The mm regime: Observations at higher frequencies are important not only for spectral studies of the variable component but also because of the reduced effect of ISS. The $\lambda^{-2.2}$ dependence of ISS in the standard model originally led to the prediction that observations in the mm regime would not be subject to scintillation-induced variations. Increased accuracy and sensitivity permitted studies of pulsars at higher frequencies and led to the identification of scintillations even at 30 GHz (Kramer et al. 1997). Revised prediction now also suggest that the scattering of the ISM may even be observable in the 3mm and possibly the 1mm band for very high column densities, as in the galactic plane (Walker, these Proceedings, page 285).

For any source above the galactic plane, the 1–3 mm regime is hence the band of longest wavelengths where no effects from ISS complicate the interpre-

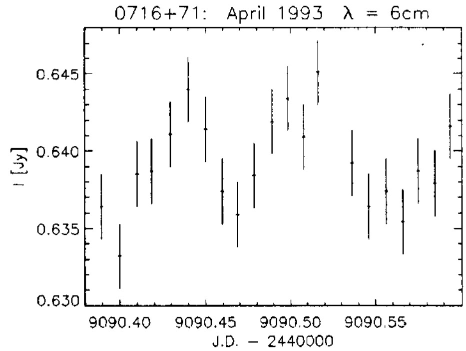

Figure 1. Fast variations in the BL Lac Object S5 0716+714 at 6 cm. The reduced χ^2 estimate for constant flux on timescales of about an hour is 5.2 (taken from Kraus et al., in preparation).

tation of variability studies as far as intrinsic effects are concerned. On the other hand atmospheric effects greatly reduce the accuracy of flux density monitoring. In a few cases, however, it is possible to investigate variability properties with useful accuracies. In an attempt to study IDV at these frequencies with the SEST telescope on La Silla, variability was detected in PKS 0405–385 (Figure 2). This source is particularly easy to study, since it is only 3 degrees away from PKS 0402–362, another flat-spectrum source which has an average flux density of about 3 Jy. Used originally as a pointing source for PKS 0405–385, it was monitored together with the latter since the flux of that object was found to vary. Hence all of the data points in Figure 2 are sandwiched between two exposures of comparable length of PKS 0402–362 which was also used to monitor the pointing and focusing. The estimated errors agree exactly with the variance of PKS 0402–362. This confirms the stability of the bolometer and the reduction as well as the estimates of the errors bars (Wagner, in preparation). Figure 2 shows very significant variations on the timescale of 2 (1) day(s) in the observers (source) frame. There even is an indication for a rise within 2 hours, but this is based on a single point only and is hence disregarded, in spite of negative results of a careful inspection for possible flaws. Although the brightness temperature derived from these observations is “only” 10^{14} K due to the higher frequency as compared to the cm variations described above, these observations clearly prove the existence of *intrinsic* IDV in this specific object, which was later found to show dramatic variations at lower frequencies (Kedciora-Chudzer et al., these Proceedings, page 267) and which have been interpreted as RISS induced variations on the basis of the frequency dependence of the modulation index. We note, that the variability index derived for our (short) period of observations lies more than an order of magnitude above the extrapolation of the lower frequency data of Kedziora-Chudzer et al. PKS 0405–385 exhibited the largest amplitude in the 230 GHz monitoring campaigns, but several other sources showed clear IDV as well (Wagner, in preparation). The upcoming multi-beam bolometers at the IRAM 30m telescope and the JCMT will permit much better corrections for weather effects and will hence allow considerable progress in this field.

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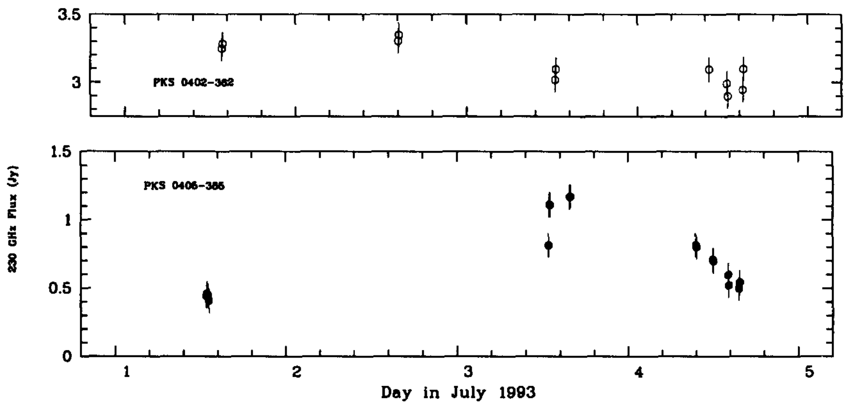

Figure 2. 230 GHz flux density variations of PKS 0405–385 (bottom panel) compared to contemporaneous monitoring of the calibration source PKS 0402–362 (top panel). The observations of the variable source PKS 0405–385 were sandwiched between those of the very close-by reference to minimize atmospheric influences and assure a quasi-simultaneous calibration.

2.2. IDV at Optical Wavelengths

Optical variations can be recorded from historical photographic sky patrol observations and thus probe long-term changes. Light-curves over more than a century have been constructed for some of the brighter quasars and BL Lac objects and some show long-term trends over more than a decade. On the other hand, variations on timescales as short as days and hours had already been discovered more than thirty years ago. Confidence in the reality of the fastest variations grew with the use of CCD detectors and simultaneous variations from independent telescopes (Wagner et al. 1990). As in the radio regime, it is possible also to study fast variations of the spectral indices and polarization characteristics as shown in Figure 3.

Spectral variations are expected due to the different variability amplitudes in different waveband regimes. In most cases the spectra become flatter during bright stages. Variations in the polarization characteristics are more important since they indicate a high degree of turbulence of the magnetic field. Temporal changes of the polarization angle during a few hours only imply that the orientation of the local magnetic field at the site of the emission high-lightened by a particular flare changes on spatial scales of a few light-hours.

The structure function of IDV blazars shows a pronounced knee on timescales of about one day with a much shallower slope towards the faster flares. After correction of the slope for measurement errors there is still a clear indication of fast variability down to the limits of the sampling (rather then the measurement errors) This led to various studies of even faster changes. In S5 0716+714 and a few other gamma-bright IDV sources we have detected flares down to timescales of 60 sec, which expands the dynamic range of variability studies to at least seven orders of magnitude in the temporal regime.

Clearly, the fastest changes provide important clues. Although the brightness temperature derived for the optical variation is not very high (10^{10} K), the

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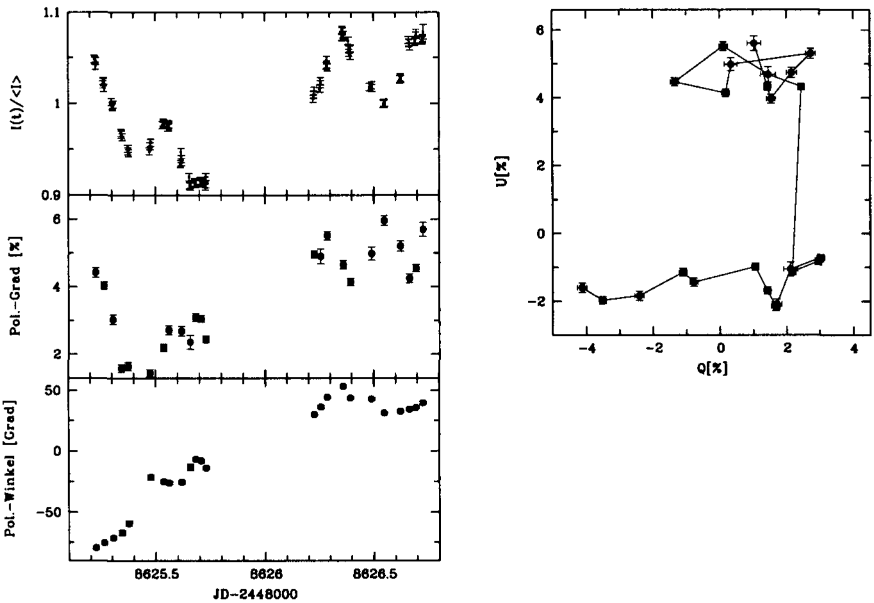

Figure 3. Total flux variations (top left) are accompanied by equally fast changes of degree of polarization (center left) and polarization angle (bottom left) in S5 0716+714 and other IDV sources. Variations correspond to cyclic paths in the Stokes plane (right panel) which do not follow any simple correlation with changes in total flux density. The rapid changes indicate clear variations of the magnetic field direction at the location of the excess emission (from Kümmel et al. 1996).

fast outbursts constrains the size of the emitting region. 20 % of the flux of these sources is emitted from a region as small as $\mathcal{D}\times$ 0.1 AU. This suggests that acceleration timescales may be more important for the characteristics of the variability than those of radiative cooling.

2.3. IDV at X-and Gamma-Ray Energies

Fast variations are known to occur in the X-ray domain already since more than a decade (e.g., WW95). As at lower frequencies, changes in flux are generally accompanied by spectral changes. In many cases the latter were found to show a soft lag, i.e. a time-delayed hardening of the spectral state, which can be modeled in a satisfactory way by Synchrotron-Self-Compton models (e.g., Takahashi et al. 1997).

During the last five years the GRO satellite opened the gamma-ray window and found many flat-spectrum radio sources to be strong emitters in the 100 MeV–2 GeV band (Mattox, these Proceedings, page 39). FSRQs and BL Lacs are the dominant source population in this regime. In many of the sources the broad-band spectral energy distributions are dominated by the gamma-emission. This result is biased however, since most of the sources turned out to show variations of high amplitudes with many of the fainter sources being detected only during strong outbursts. The strongest flares reached flux-densities of several photons per hour, and hence allowed investigations on timescales as short as days (e.g., Mattox et al. 1997). In all of those cases, the flux turned out to be variable as shown by statistical studies of gamma-ray IDV by means of structure function analyses (Wagner et al. 1997).

Even more recently the energy threshold has again been increased by another three orders of magnitude and the TeV window has been opened with the successful operation of ground-based atmospheric Cherenkov-Telescopes and -Arrays. At least two BL Lac objects—Mrk 421 and Mrk 501—have been repeatedly detected by three groups, all of them reporting variability on scales of years and weeks down to the fastest changes which can be probed with current sensitivities (about tens of minutes during bright stages when fluxes of a few photons per minute can be recorded, e.g., Wagner 1997).

2.4. Correlations Between Different Wave-Bands

As described in Section 2.3, the sources exhibiting IDV at radio frequencies have been found to vary in flux down to the shortest timescales probed so far throughout the entire electromagnetic spectrum. Whenever measured with sufficient accuracies, total flux variations are accompanied by variations of spectral indices and polarization properties. The broad-band nature of the spectral energy distribution suggests that one or only a few processes are responsible. One would hence predict the variations in the individual bands to be correlated. Many attempts to derive correlation functions in order to constrain physical parameters have been carried out recently.

Radio- vs. Optical Variations Many campaigns were carried out throughout the eighties to derive the cross-correlation function between optical and radio light curves of radio-loud quasars. In general a fair amount of correlation was found at lags of the order of a few months or less. The derived lags increase considerably for lower frequencies and higher luminosities. For IDV sources close correlations between optical and radio flux have been found with vanishing lags only (Quirrenbach et al. 1991; Wagner et al. 1993; Wagner et al. 1996). Correlations of optical flux with radio spectral index (Wagner et al. 1996) show that formal lags strongly depend on the frequency chosen. The break-frequency at which these correlations set in depend on the (slowly changing) overall spectral shape in the radio domain. Hence, the existence of close correlations between optical flux and radio-flux at any given frequency changes. This explains the observation that not all simultaneous campaigns reveal correlated variations between the optical flux and radio flux at, e.g., 5 GHz.

Optical vs. X-/γ-Ray Variations Close correlations with vanishing lags have been found in a few densely sampled campaigns (e.g., Edelson et al. 1995). As with radio/optical correlations, repeated campaigns on the same source revealed different variability patterns and very different correlation functions. Georganopoulos et al. (1997) illustrate that these discrepancies may be understood by different overall states with changes in the high-energy cutoff of the synchrotron branch. Close correlations have also been found between optical and gamma-ray emission in several flat-spectrum sources including PKS 0420–014, PKS 0528+134, S5 0836+71, 3C 279, PKS 1406–076, as reviewed e.g., by Wagner (1997). Correlation functions are difficult to derive due to low gamma-ray flux densities, under-sampling in either band (even one-day sampling being clearly insufficient) and—again—variations of the intrinsic characteristics during different epochs. Nevertheless, close temporal relations with vanishing lags but very different amplitude scalings emerge as a general trend. Interestingly, one case was reported (Wagner et al. 1995) with gamma-rays lagging behind *after* the optical flare.

3. Intrinsic and Extrinsic Effects

It is important to consider the extrinsic effects which may introduce flux variability and mimic intrinsic changes of flux density. The very wide range of frequencies over which comparable variability characteristics are observed suggests that an achromatic mechanism, such as micro-lensing, is a prime candidate. Changing amplification of the flux emitted from a background source due to the gravitational lensing of (sub-) stellar-mass objects may have been detected in macro-lensed objects (see, e.g., in Kochanek & Hewitt 1996). In IDV sources many statistical properties disagree with predictions of micro-lensing. These include the absence of lensing galaxies, the short timescales, the statistical asymmetries of the light-curves, the shapes of individual flares, etc. (WW95). The high duty cycles could only be produced by micro-lensing in the optically thick limit, in case of which macro-lensing is predicted (but not detected). Micro-lensing can hence be ruled out as the dominant cause for IDV.

IDV at low frequencies may be influenced considerably by ISS (Rickett, these Proceedings, page 269). Walker (these Proceedings, page 285) suggest that RISS may be important for very high column densities even up to 100 GHz. Several of the observed characteristics do not agree with predictions from RISS. Modeling of IDV (e.g., Rickett et al. 1995) suggest relative velocities of the ISM which are comparable to the earth's orbital velocity and hence predict seasonal variations of variability properties as observed for LFV (Bondi et al. 1994) which are not seen in IDV sources. Pronounced variations at 230 GHz from sources well above the galactic plane (such as PKS 0405–385, Figure 2) cannot be due to ISS either. Even higher frequencies (such as the optical band) are completely unaffected by RISS. Correlated optical/radio variations are hence another clear indication to rule out RISS as the only cause for IDV. The same applies for the agreement of statistical properties of IDV sources in these two frequency regimes. Since any source which exhibits intrinsic IDV subtends a very small angle on the sky only, it is necessarily subject to scintillation on some level. Any detailed investigation will hence require RISS-induced and intrinsic variability to be disentangled.

4. Implications

Intrinsic, fast variations of the total and polarized flux is seen over the entire accessible part of the electromagnetic spectrum down to the shortest timescales probed so far. There is little evidence for periodicity but breaks in the structure functions indicate preferred regime, probably separating different modes (which presumably emerge from different regimes in the jet). IDV is closely correlated over a wide range in energy and across the gap separating the synchrotron and high-energy (Compton scattered) regime.

The fast changes of the polarization characteristics suggest small scale turbulence of the magnetic field at the site of excess emission. The large amplitudes of the polarization argue at the same time against very large numbers of individual cells, indicating the the timescales of variations correspond approximately to the length-scales of the turbulent magnetic field. It is interesting to note that the close match of optical and gamma-ray flares also suggests that the timescales of variability correspond to particle acceleration times rather than radiative processes.

Since the fastest variations imply brightness temperatures up to 10^{19} K even the maximum boosting of jets with low radiative efficiency, $\mathcal{D} \sim 100$, is insufficient to avoid the limit of the Compton catastrophe ($10^{12} \times \mathcal{D}^3$). This suggests either that (part of) the radio emission is coherent or that very special geometric conditions apply.

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