CHAPTER THREE

Intra-Day Variability, Gravitational Lensing and Polarization

https://doi.org/10.1017/S0252921100000750 Published online by Cambridge University Press

RADIO INTRA-DAY VARIABILITY: ANSWERS AND QUESTIONS

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Abstract. Intra-day variability (IDV) of active galactic nuclei (AGN) has been detected from gamma-ray energies to radio wavelengths. At high energies, such variability appears to be intrinsic to the sources themselves. However, at radio wavelengths, brightness temperatures as high as 10^{18} to 10^{21} K are encountered if the IDV is intrinsic to the source. We discuss here the accumulating evidence showing that, at radio wavelengths where the highest brightness temperatures are encountered, interstellar scintillation (ISS) is the principal mechanism causing IDV. While ISS reduces the implied brightness temperatures, they still remain uncomfortably high.

1. Introduction

Since its discovery (Dent, 1965) the radio variability of extragalactic radio sources has been a powerful indicator of the presence of compact source structure. Several

Astrophysics and Space Science **278:** 87–92, 2001.

decades of VLBI observations have confirmed that these month to year time scale variations are intrinsic and revealed a close relationship between structural changes on pc scales and flux density changes. It was noted (Kellermann and Pauliny-Toth, 1969) that inverse Compton losses would limit brightness temperatures to no more than 10^{12} K. Bulk relativistic motion (Rees, 1966) was confirmed with the discovery of apparent super-luminal motion in AGN. However, VLBI monitoring of the internal proper motions of large samples of flat-spectrum sources shows that brightness temperatures should be limited to no more than 10–20 times the inverse Compton limit (Marscher *et al.*, 2000; Kellermann *et al.*, 2000).

Following Dent's discovery, observations at mm, optical, X-ray and Gamma-ray wavelengths revealed more rapid variability with time-scales of days to hours (Wagner and Witzel, 1995, and references therein). To search for possible intra-day variations at radio wavelengths, Heeschen undertook a careful search using the Green Bank 90 m telescope at 3.3 GHz (Heeschen, 1984). He discovered significant variability, up to 7.5% rms, amongst the flat-spectrum sources in his sample, and called these variations *flickering*. The flat-spectrum sources flicker much more strongly than steep-spectrum sources. Intensive campaigns with the Bonn 100 m telescope, and later with the VLA, demonstrated that many sources show intra-day variability (IDV), as this phenomenon is now called (Witzel *et al.*, 1986).

This demonstrated that rapid variability on time-scales of days or less occurs over the entire wavelength range. If intrinsic to the source, then the implied brightness temperatures at radio wavelengths are as high as 10^{21} K in extreme cases (Kedziora-Chudczer *et al.*, 1997), well in excess of that allowed by the limited apparent velocities seen by VLBI. In order to avoid such extremes, interstellar scintillation (ISS) was suggested as a possible mechanism (Heeschen, 1984; Heeschen and Rickett, 1987). It should be remembered that any AGN that shows intrinsic variability is sufficiently small that it must also scintillate in the interstellar medium (ISM). Interstellar scintillation must be at least a component of IDV at radio wavelengths.

If the variability is intrinsic, causality arguments imply light day to light hour physical sizes, nano-arcsecond angular sizes and brightness temperatures as high as 10^{21} K. Alternatively, ISS implies micro-arcsecond angular sizes and brightness temperatures up to 10^{14} to 10^{15} K, extreme, but considerably less so than if the variations are intrinsic. Because of the large differences in brightness temperature it is essential to establish which of the competing mechanisms is in operation.

2. Evidence for Interstellar Scintillation

In his discovery paper Heeschen (1984) concluded that the flickering is probably not correlated with Galactic latitude, as might be expected for ISS, and suggested both intrinsic and ISS as possible causes. A later re-examination of the original observations, however, revealed a significant latitude dependence consistent with its being the result of ISS (Heeschen and Rickett, 1987).

Additional support for ISS comes from the strong frequency dependence observed for IDV. For an ISS origin, this is expected in the transition from weak scattering to strong scattering at a frequency that is latitude dependent, but usually around 2–3 GHz for mid-latitude sources (Walker, 1998). Examples of the variability patterns can be seen in observations at 15, 8, 5, 2.7 and 1.4 GHz of the strong IDV source 0917+624 (Rickett *et al.*, 1995). Moreover, their detailed analysis demonstrates that the individual light curves at the lower frequencies can be accurately derived from the 15 GHz light curve. This is good evidence to support ISS in this source.

Further examples can be seen in the most rapidly variable sources PKS0405–385 (Kedziora-Chudczer *et al.*, 1997) and J1819+3845 (Dennett-Thorpe and De Bruyn, 2000). Both show rapid and highly correlated variability at 5 to 8 GHz. At frequencies below 2.3 GHz, the variability time-scale dramatically increases, and there is no correlation between the variations at 1.4 and 2.3 GHz, Kedziora-Chudczer *et al.*, found that the variation of modulation index with frequency for PKS0405–385 was very well described by ISS with a simple one-parameter model over the frequency range 1.4 to 22 GHz.

However, it not always as simple as the above cases might imply. The VLA data of Quirrenbach *et al.* (2000) shows overall that the variations are strongest at 5 GHz and weaker at both 1.5 and 15 GHz, but there remain several sources for which the above simple picture does not apply. For example, 0716+714 shows a change in the character of the IDV with time as the overall radio spectrum evolves. Scintillation explanations need to postulate evolution of the radio spectra of the scintillating components with time, which is perhaps not unexpected given the microarcsecond component sizes implied.

We have addressed the issue of an intrinsic versus extrinsic origin through the search for a time-delay in the arrival times of the variability pattern at two widely spaced telescopes, the VLA in western USA and the ATCA in eastern Australia. These two large array telescopes allow rapid, high-precision flux density measurements to be made in a straight forward manner. Different patterns may be discerned and a precision of a few tens of seconds may be achieved in searching for any time delay.

PKS0405–385 is a strong IDV source with an unusually short characteristic time-scale of $\sim$ 1 hour and variability amplitude of up to 1 Jy (Kedziora-Chudczer *et al.*, 1997). The observations were made at 5 GHz in December 1998, two weeks after we had found that large-amplitude, rapid variability had re-appeared in this source (Kedziora-Chudczer *et al.*, 1998). The outburst is described by Kedziora-Chudczer *et al.*, in these proceedings. We saw strong variability with very similar patterns at both telescopes, and were fortunate to observe a minimum in the variability pattern. There is a significant difference in the arrival times of the patterns of 140 $\pm$ 25 seconds between the two telescopes. The uncertainty was established through a long series of Monte Carlo trials (Jauncey *et al.*, 2000). This is strong direct evidence of an ISS origin for the IDV in PKS0405–385.

Additional strong, direct evidence can be found in the observed one-year signature in the time-scale of the long-term variability pattern observed for J1819+3845 (Dennet-Thorpe and De Bruyn, this symposium). Moreover, this one-year signature appears for an additional source (Rickett, this symposium), providing further direct evidence in support of an ISS origin for radio IDV.

3. New Questions

While an ISS origin for radio IDV answers many of the questions regarding source properties, nevertheless serious questions remain.

In exploring the intrinsic hypothesis, a variety of models have been developed (Qian *et al.*, 1991). The VLBI experience has shown conclusively that the longer time-scale variability is intrinsic, so it was natural to extend this to the shorter time-scales of IDV. Several multi-wavelength campaigns were undertaken to search for correlated radio and optical IDV as an indication that the rapid radio variation is not caused by ISS. The correlated radio and optical variability reported for the BL Lac object 0716+714 (Quirrenbach *et al.*, 1991; Wagner *et al.*, 1996) is the strongest evidence presented *for* intrinsic variability and *against* an ISS origin. Despite the accumulation of strong evidence for an ISS origin, these correlations need to be understood in ISS terms before it can be fully accepted as the origin of radio IDV.

The presence of ISS points directly to microarcsecond source angular sizes and brightness temperatures of 5×10^{14} K (Kedziora-Chudczer *et al.*, 1997). These are considerably less extreme than the nanoarcsecond sizes and 10^{21} K values were the variations intrinsic, but nonetheless remain considerably in excess of the 10^{12} K inverse Compton limit. However, space VLBI observations with VSOP have shown directly the presence of brightness temperatures of up to 10^{13} K in many flat-spectrum sources (Lovell *et al.*, 2000).

The distance to the equivalent scattering screen is a critical parameter in determining the brightness temperature, since it scales as the screen distance (Walker, 1998). Kedziora-Chudczer *et al.* (1997) assume a screen distance of half the halo scale height, 500 pc, to derive a 5×10^{14} K brightness temperature for extreme IDV in the source PKS0405–385. However, Dennett-Thorpe and De Bruyn (2000) use a value of 30 pc for the screen distance for the weaker but more rapidly variable IDV source J1819+3845, for a brightness temperature of 5×10^{12} K.

The high T_b values imply Lorentz factors of 10^3 in order to be explained by bulk relativistic motion (Readhead, 1994). While values of 10–20 are consistent with existing VLBI observations, 10^3 remains unacceptable (Marscher *et al.*, 2000; Kellermann *et al.*, 2000). There clearly is a need for more reliable screen distances before more accurate brightness temperatures for IDV sources can be determined.

There are also difficulties with the high observed frequency of occurrence of IDV. Surveys detect IDV in at least $\sim 25\%$ of all flat-spectrum sources (Heeschen, 1984; Quirrenbach *et al.*, 1992; Kedziora-Chudczer *et al.*, 2000), and it may be more common, as suggested by the Pearson-Readhead Survey from space (Preston *et al.*, 2000) and the preliminary VSOP Survey results (Lovell *et al.*, 2000). Even for an ISS origin, this poses problems, since this implies far too many sources that are beamed particularly closely towards us. For an intrinsic origin, and the resultant super-high brightness temperatures, it is even more difficult to explain the observed high fraction of IDV sources.

These problems are compounded with the lifetimes of some IDV sources. For example, 0917+624 and PKS1519–273 appear to have shown radio IDV every time they were looked at in detail over the last 10–15 years. For brightness temperatures of up to 5×10^{14} K, the synchrotron lifetimes implied are significantly less than those observed (Readhead, 1994).

Finally, the surprising presence of strong and variable circular polarization in PKS1519–273 (Macquart *et al.*, 2000 and this symposium) and in PKS0405–385 (Kedziora-Chudczer *et al.*, this symposium), add further to the difficulties. While ISS appears to provide an answer as to the major source of IDV, at the same time it raises further serious questions.

Acknowledgements

The Australia Telescope is funded by the Commonwealth Government for operation as a national facility by CSIRO. The National Radio Astronomy Observatory is operated by Associated Universities Inc., under cooperative agreement with the National Science Foundation. The Special Research Centre for Theoretical Astrophysics was funded by the Australian Research Council under its Special Research Centres Programme.

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