Astrophysical Letters
1977, Vol. 18, pp. 109–113

Intensity Variations of DW 1548+05 at 2.7, 6.6 and 10.6 GHz

A. H. BRIDLE *Queen's University at Kingston, Ontario K7L 3N6, Canada and Institute of Astrophysics, Erin, Ontario*

(*Received November 30, 1976; in final form January 20, 1977*)

The "flat-spectrum" radio source DW 1548+05 is shown to have varied significantly in intensity at 2.7 GHz, despite the lack of convincing evidence for variability at higher frequencies. The interpretation of such sources as inhomogeneous objects in which different regions become optically thick at different frequencies is not compromised by the apparent lack of high-frequency variability. The advantages of observing at frequencies below 5 GHz should not be overlooked when implementing monitoring programs intended to place constraints on source models.

INTRODUCTION

Gearhart *et al.* (1976) have recently rediscussed the problem of understanding the straight-spectrum radio sources with spectral indices $\alpha \sim 0$, a class of source exemplified by the 18^{m} stellar object DW 1548+05 (Davis, 1967). The flux densities of DW 1548+05 available in 1968 were within experimental error of 2.8 Jy at each of 0.178, 0.75, 1.4, 3.2, 6.6 and 10.6 GHz (Bridle, 1969); subsequent observations at 0.318 and 0.6 GHz (Jauncey *et al.*, 1970) supported this apparent constancy of flux density with frequency.

If the apparent spectral simplicity is assumed to be real (and not an accident of discrete frequency sampling) such sources could be interpreted either as structurally simple systems with optically thin radio components and relatively flat electron energy spectra ($dN \propto E^{-1}\,dE$) or as inhomogeneous systems in which different emitting regions become optically thick at different frequencies so that the radio spectrum does not reflect the electron energy spectrum (Williams and Bridle, 1967). Kellermann *et al.* (1971) gave evidence that the overall angular size of DW 1548+05 is $\lesssim 0.015$ arc sec at 0.6 GHz and that 40 percent of the intensity between 2.3 and 5 GHz is $\lesssim 0.001$ arc sec in diameter. With these parameters the "simple-source" assumption of small optical depth at the low-frequency end of the measured spectrum implies very small magnetic field strengths ($\lesssim 10^{-8}$ gauss). On these and other grounds Jauncey *et al.* (1970) supported the inhomogeneous-source interpretation.

Gearhart *et al.* (1976) emphasize however that most optically-thick source components vary in intensity whereas the total flux density of DW 1548+05 has shown little evidence for variability over four years of monitoring at 6.6 and 10.6 GHz at the Algonquin Radio Observatory (Medd *et al.*, 1972; Andrew *et al.*, 1976). This observation appears to place constraints on inhomogeneous-source models. This Letter argues however that an accident of frequency choice and timing of observations has prevented the variability of DW 1548+05 being detected in the Algonquin monitoring program.

OBSERVATIONS AT 2.7, 6.6 AND 10.6 GHz

I observed DW 1548+05 occasionally between 1968 and 1972 at 6.6 and 10.6 GHz using the 150-ft (46-m) telescope at the Algonquin Radio Observatory. The equipment, observing procedure and calibration were essentially as described by Bridle (1969) and by Brandie and Bridle (1974). The adopted flux-density scale is within measurement error of that used by Medd *et al.* (1972) in the main Algonquin program. A few of the early measurements were made in only one linear polarisation, but as DW 1548+05 never showed linear polarisation >2 percent during over 3 years of 8.1-GHz monitoring by Altschuler and Wardle (1976) it is unlikely that comparison of flux densities in different polarisations would introduce errors comparable to the other errors of measurement.

For two years beginning in September 1972, DW 1548+05 was included in an extensive 2.7-GHz monitoring program at the NRAO 300-ft (91-m) telescope by M. J. L. Kesteven, G. W. Brandie and me; the observing and calibration procedures were

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TABLE 1

Flux densities of DW 1548+05 at three frequencies

	10.6 GHz-ARO			2.7 GHz-NRAO	
Date	Flux density (Jy)	Ref.	Date	Flux density (Jy)	Ref.
29 May 68	2.80±0.35	1	1 Jan 72	2.21±0.08	3
12 Aug 68	2.70±0.20	1	18 Apr 72	1.89±0.11	3
20 Mar 69	2.30±0.20	1	19 May 72	2.07±0.08	3
20 Jan 70^a	2.37±0.15	2	17 Jun 72	2.00±0.08	3
11 Mar 70^a	2.16±0.15	2	7 Sep 72	1.92±0.05	1
3 May 70	2.08±0.25	1	9 Sep 72	1.95±0.04	1
19 May 70^a	2.04±0.15	2	29 Oct 72	1.93±0.07	3
18 Sep 70^a	2.25±0.15	2	21 Jan 73	1.86±0.02	1
23 Oct 70	2.19±0.15	2	12 Apr 73	1.94±0.03	1
24 Oct 70^a	1.80±0.30	1	13 Apr 73	1.90±0.02	1
11 Jan 71^a	2.11±0.15	2	19 Apr 73	1.89±0.07	3
18 Apr 71^a	2.21±0.15	2	31 May 73	1.95±0.08	3
22 Jun 71	1.96±0.15	1	28 Jun 73	1.94±0.07	3
17 Jan 72	2.15±0.20	1	4 Aug 73	2.09±0.08	3
11 Mar 72	2.48±0.15	1	25 Aug 73	2.07±0.02	1
17 May 72	2.38±0.12	1	9 Sep 73	1.97±0.07	3
13 Jul 72	2.13±0.10	1	18 Oct 73	2.08±0.08	3
			24 Nov 73	2.14±0.08	3
	6.6 GHz-ARO		26 Dec 73	2.23±0.10	3
			1 Feb 74	2.24±0.08	3
11 Aug 68	3.25±0.30	1	5 Feb 74	2.12±0.03	1
23 Mar 69	2.65±0.25	1	6 Mar 74	2.14±0.08	3
28 Mar 69^a	2.52±0.10	2	1 Apr 74	2.14±0.08	3
19 Mar 70^a	2.37±0.10	2	27 May 74	2.08±0.08	3
30 Apr 70	2.15±0.20	1	14 Jun 74	2.07±0.03	1
28 Jun 70	2.14±0.07	1	23 Jun 74	2.08±0.02	1
18 Sep 70^a	2.25±0.10	2	4 Aug 74	2.16±0.02	1
25 Sep 70	2.23±0.20	1	22 Oct 74	2.32±0.08	3
7 Nov 70	2.24±0.10	1	17 Nov 74	2.24±0.08	3
11 Jan 71^a	2.42±0.10	2	18 Jan 75	2.23±0.08	3
4 Mar 71^a	2.21±0.10	2	18 Mar 75	2.22±0.08	3
17 Dec 71	2.15±0.17	1	4 May 75	2.39±0.08	3
			16 Jun 75	2.33±0.08	3

Key to references: 1—This paper; 2—Medd *et al.* (1972); 3—Altschuler and Wardle (1976).

(^{a}) Average of date interval given by the authors.

described in detail by Kesteven *et al.* (1976). These 300-ft observations were overlapped by less precise but more frequent 2.7-GHz observations at the NRAO 3-element interferometer by Altschuler and Wardle (1976). Dr. Wardle and I have established that, after allowing for an apparent variation of the efficiency of the interferometer with elevation, the 2.7-GHz flux densities measured concurrently at the interferometer and at the 300-ft are in excellent agreement. The interferometer elevation correction for DW 1548+05 is less than 1 percent, so for this source the 300-ft data can be compared directly with the *published* (uncorrected) interferometer data.

Table 1 lists my 10.6 and 6.6-GHz data for 1968–1972 together with that of Medd *et al.* (1972) for same period. It also lists the combined 300-ft and interferometer data at 2.7 GHz between 1972 and mid-1975.

VARIABILITY AT 2.7, 6.6 AND 10.6 GHz

Figure 1 plots the 2.7-GHz data in time series. The flux density slowly declined from ~2.2 Jy at the beginning of 1972 to <1.9 Jy in January 1973. From mid-1973 to mid-1974 there is the *appearance* of a slow "burst" of amplitude ~0.3 Jy, after which

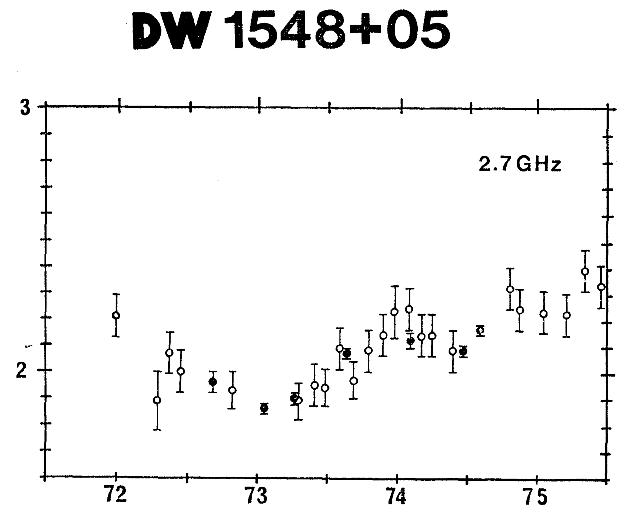

FIGURE 1 Plot of 2.7-GHz data from Table 1 in time series. Filled circles: 300-ft data. Open circles: interferometer data. Where data points would overlap they have been slightly displaced in time if from different instruments and one has been omitted if from the same instrument. The flux-density units are Janskys.

the flux density gradually increased to ~2.3 Jy by mid-1975. The data from the 300-ft telescope and from the interferometer independently show the variations. The significance of the variations in the combined data set was examined by computing the statistic

$$x^2=\sum_{i=1}^{n}(S_i-\bar{S})^2/\sigma_i^2,\quad \bar{S}=\sum_{i=1}^{n}(S_i/\sigma_i^2)\Big/\sum_{i=1}^{n}(1/\sigma_i^2)$$

where S_i and σ_i are the ith flux density and its error. In the presence of random noise alone x^2 has a χ^2 distribution with $(n-1)$ degrees of freedom. The 2.7-GHz data have $x^2 = 295.2$; the probability of exceeding this value of x^2 by chance in a data stream with $n = 33$ is $\leqslant 10^{-6}$. The variations are thus highly significant.

All of the NRAO 2.7-GHz flux densities lie significantly below the value of 2.76 ± 0.14 Jy measured by Witzel *et al.* (1971) with the Nançay reflector at an unspecified date between December 1967 and June 1970. Shimmins *et al.* (1975) observed a 2.7-GHz flux density of 1.83 ± 0.07 Jy with the Parkes telescope in December 1972; this value is in agreement with the low flux densities observed at NRAO at this time. Bridle *et al.* (1977) have demonstrated that the NRAO 2.7-GHz flux-density scale is in good agreement with the Nançay and Parkes scales, so it seems beyond reasonable doubt that DW 1548+05 has varied at 2.7 GHz, possibly by as much as 1 Jy since the late 1960s.

Figure 2 plots the 6.6 and 10.6-GHz data in time series. The lack of significant variations between 1970 and mid-1972 is unaltered by adding my data to the published Algonquin measurements; it is also confirmed by the x^2 test. At both frequencies there is evidence that by early 1970 the flux densities had declined to ~2.2 Jy from the values reported in Bridle (1969) but the statistical significance of this evidence is marginal (due to the large uncertainties in the earliest measurements). The probability of exceeding the *overall* 10.6-GHz x^2 (= 22.9) by chance is 0.12. The probability of exceeding the 6.6-GHz x^2 (= 26.8) is only 0.005 but the earliest measurement contributes $x^2 = 10.1$ and the remaining data are not significantly scattered.

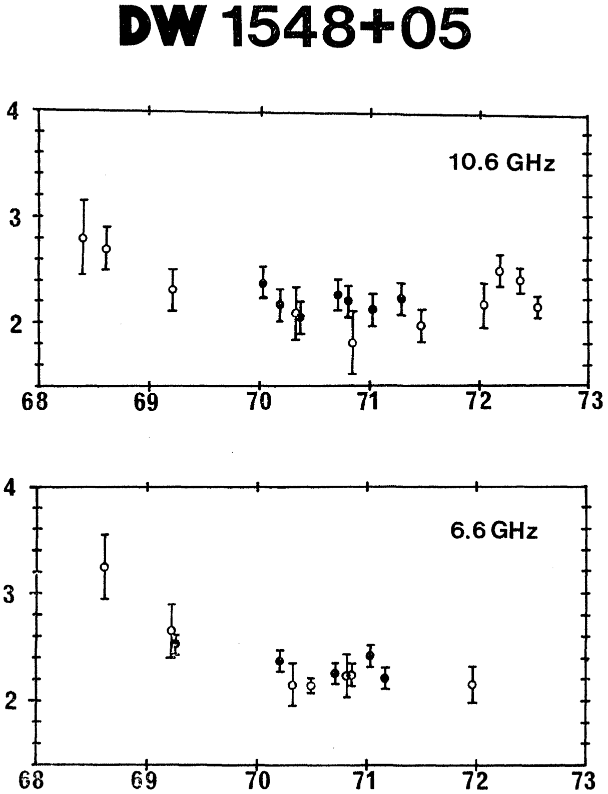

FIGURE 2 Plot of 10.6 and 6.6-GHz data from Table 1 in time series. Filled circles: data from Medd *et al.* (1972). Open circles: the present observations. Some adjacent points have been slightly displaced in time for clarity. The flux-density units are Janskys.

OTHER EVIDENCE FOR VARIATIONS

Neither the 8.1-GHz monitoring ($x^2 = 19.5, n = 22$) during 1972–75 by Altschuler and Wardle (1976) nor the 15.5-GHz monitoring ($x^2 = 29.4, n = 19$) during 1970–72 by Dent *et al.* (1974) show significant variations. At 5 GHz however Pauliny-Toth and Kellermann (1968) observed 2.54±0.06 Jy at epoch 1967.3 whereas Shimmins *et al.* (1975) found 2.18±0.08 Jy in December 1972. Although different telescopes were used for these 5-GHz measurements, DW 1548+05 is a small-diameter source and is not confused at 1.4 GHz (Bridle *et al.*, 1972), so the 5-GHz decrease indicated by these results is likely to be real. At 1.4 GHz Davis (1967) measured 2.8±0.1 Jy at the NRAO 300-ft telescope between 17 February and 4 April 1966 whereas Bridle *et al.* (1972) measured 2.52±0.07 Jy with the same instrument in February 1970; there may however be an offset of as much as 0.1 Jy between the two sets of data (Bridle *et al.*, 1972) so the significance of this apparent decrease is less certain.

The most striking evidence for a flux-density decrease at other than 2.7 GHz since the late 1960s is the fact that *all* post-1970 measurements lie below the mean spectrum of DW 1548+05 defined by all pre-1970 measurements above 1 GHz. Furthermore, both Nicolson (1973) and Pauliny-Toth and Kellermann (1968) reported observing variations at 2.3 and 5 GHz respectively, although they did not document their nature, duration or statistical sigficance. It therefore appears probable that the apparent lack of variations above 5 GHz since 1970 is an accident of observing frequency and timing of the various sets of observations.

EVIDENCE FOR A PEAKED INSTANTANEOUS SPECTRUM

There were many observations of DW 1548+05 at 2.7, 6.6, 8.1, 10.6 and 15.5 GHz throughout 1972 (this paper; Altschuler and Wardle, 1976; Andrew *et al.*, 1976; Dent *et al.*, 1974). These observations bear on the important question of whether complexity is ever indicated by the appearance of peaks in the spectrum. The *highest* of eight flux densities measured by Dent *et al.* at 15.5 GHz in 1972 was 2.03±0.09 Jy (1 May); the *lowest* of six measured by Andrew *et al.* (1976) at 10.6 GHz in 1972 was 2.10±~0.1 Jy (3–14 January), and their 10.6-GHz flux densities at times near the 15.5-GHz "maximum" were ~2.2 Jy. Thus throughout 1972 DW 1548+05 appears to have had an instantaneous spectrum in which the 10.6-GHz flux density *exceeded* that at 15.5 GHz. The flux-density minimum at 2.7 GHz near the end of 1972 was certainly <1.9 Jy however, *lower than any* of the twenty flux densities measured during 1972 at 6.6, 8.1 and 10.6 GHz. It therefore seems fairly well established that towards the end of 1972 DW 1548+05 had an instantaneous flux-density maximum at a frequency above 2.7 GHz and below 10.6 GHz. The occasional presence of such maxima is a necessary but not sufficient condition for viability of the optically-thick, inhomogeneous-source models. The mid-1968 data of Bridle (1969), though of relatively low accuracy, also indicate such a peaked spectrum.

DISCUSSION

The following inferences are drawn from the above:

1) DW 1548+05 *definitely varies at 2.7 GHz* and *probably varied at higher frequencies before January 1970*. The apparent lack of variations during the Algonquin monitoring after January 1970 is not typical of this source's behaviour at all frequencies and all times.

2) The 2.7-GHz data could be interpreted as a superposition of three "bursts", one declining in intensity from 1972 onwards, a second reaching maximum intensity in late 1973 or early 1974, and a third increasing in intensity throughout 1974–75. Such an interpretation could be made quantitative only if there were detailed spectral and structural observations at these epochs. It seems likely however that DW 1548+05 is capable of varying significantly on time scales of about 1 year. This being so, the apparent lack of variation above 2.7 GHz since 1970 may be due to a combination of factors: (i) chance smoothing of its variations by *burst superposition*, (ii) *low burst amplitudes at high frequencies* in relation to those at 2.7 GHz, and (iii) *discrete sampling* of its light curve by the various observers. The last factor is unlikely to be significant in the 8.1 or 15.5-GHz monitoring, so at least one of the first two factors is probably involved at all high frequencies.

3) The present spectral and variability data do not by themselves place strong constraints on models of the source, though a multiple-component model seems favoured. The intensity history of DW1548+05 in fact exemplifies the difficulty of placing constraints on theory based on *lack* of variability, even

after assiduous monitoring at high frequencies. *The strongest constraints come from the observations of fine structure at milli-arc-sec resolution*, as noted by Jauncey *et al.* (1970). Multi-frequency and multi-hour-angle studies with very-long-baseline interferometers may offer the most reliable path towards credible models of this class of source.

4) *Frequencies below 5 GHz should not be neglected* in such monitoring programs as are undertaken in the future. The standard expanding-cloud models of variable sources are not so secure that we can be sure that variability amplitudes will always be *significantly* smaller at lower observing frequencies. Indeed, Kesteven *et al.* (1977) conclude that only a restricted class of source—opaque sources with modest fractional variabilities—*do* exhibit the variation of burst amplitude with frequency that is predicted by the standard models. Studies of variability at frequencies near 3 GHz can take advantage of the availability of larger instruments with more sensitive and stable receivers, plus increased freedom from atmospheric noise. Such advantages may partially offset the theoretically-anticipated merits of the higher frequencies for systematic monitoring programs.

ACKNOWLEDGEMENTS

I thank G. W. Brandie, M. J. L. Kesteven, R. M. Kesteven, A. E. Niell and D. G. MacDonell for their part in the observations, and the Canadian Astronomical Society for its support of the Erin Institute of Astrophysics where part of this work was carried out. The National Radio Astronomy Observatory is operated by Associated Universities Inc. under contract with the National Science Foundation. The Algonquin Radio Observatory is operated by the National Research Council of Canada, which also supported this work through an operating grant to the author.

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